Neutrino Oscillations with MINOS

Jeff Hartnell

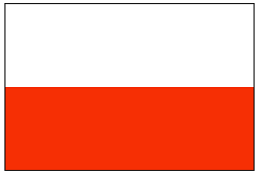
University of Sussex

for the MINOS collaboration

Introduction

- MINOS physics goals
- NuMI neutrino beam
- MINOS detectors
- Results:
  - Muon neutrino disappearance analysis
  - Electron neutrino appearance analysis (new!)
  - Neutral current analysis: sterile neutrino mixing
- Future plans

The MINOS Collaboration

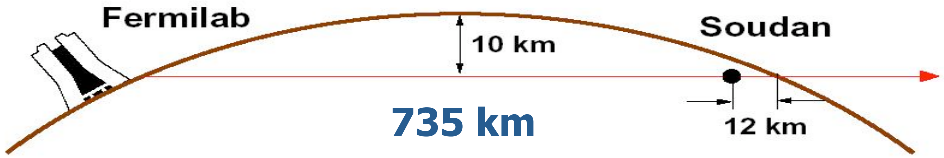


28 institutions
140 scientists

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab Harvard • Holy Cross • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Otterbein Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M Texas-Austin • Tufts • UCL • Warsaw • William & Mary

MINOS Overview

- Main Injector Neutrino Oscillation Search
- Neutrinos at the Main Injector (NuMI) beam at Fermilab
- Two detectors:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - search for and study oscillations



MINOS Physics Goals

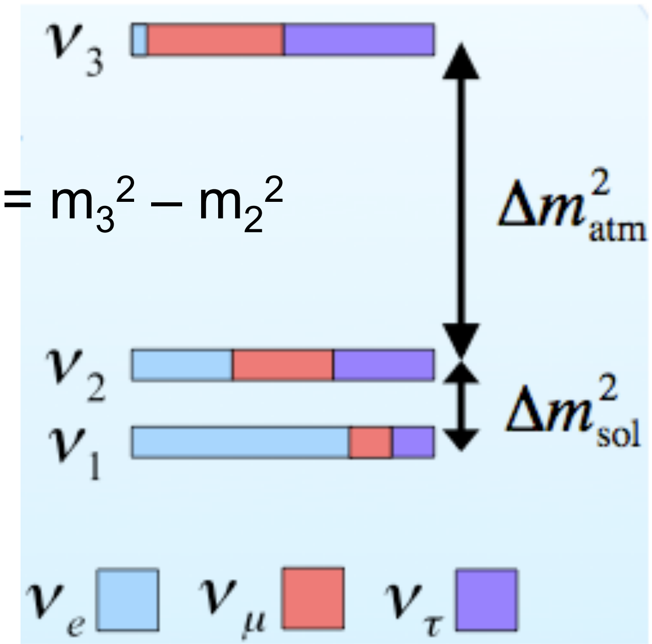
- Test the $\nu_\mu \rightarrow \nu_x$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
  - sensitive to θ_{13}
- Other MINOS physics:
  - Search for sterile neutrinos, CPT/Lorentz violation
  - Compare ν_μ, $\overline{\nu_\mu}$ oscillations
  - Studies of cosmic rays and atmospheric neutrinos
  - Neutrino interaction studies in the Near detector

ν_e appearance

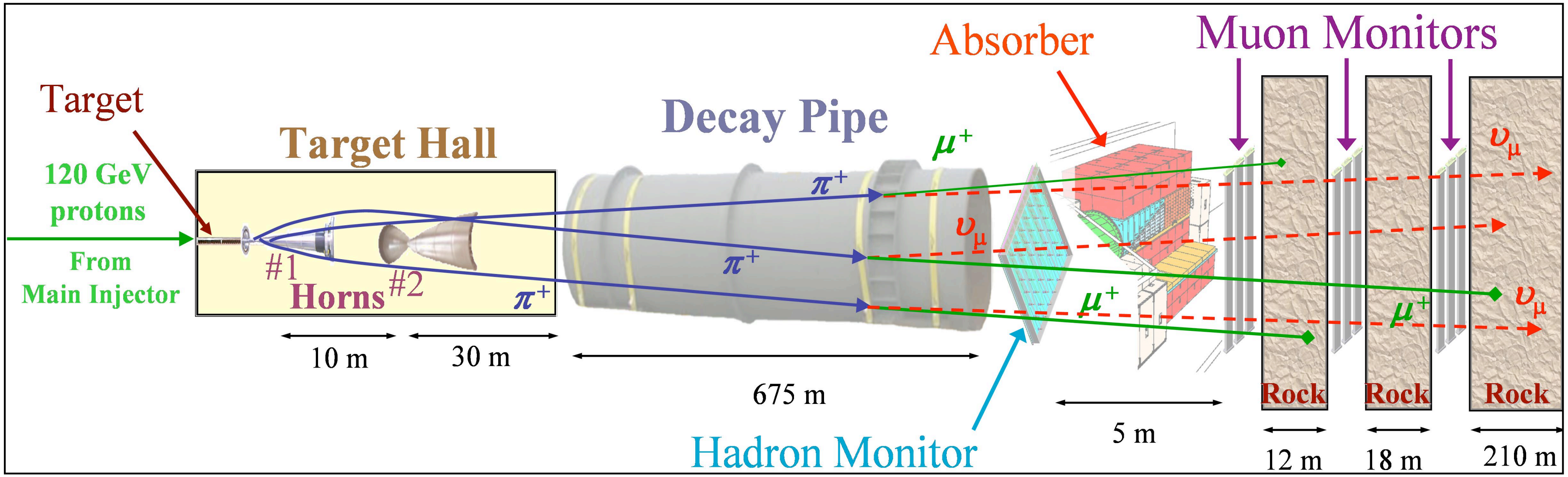
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} \\ U_{\mu 1} & U_{\mu 2} & \boxed{U_{\mu 3}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_μ disappearance

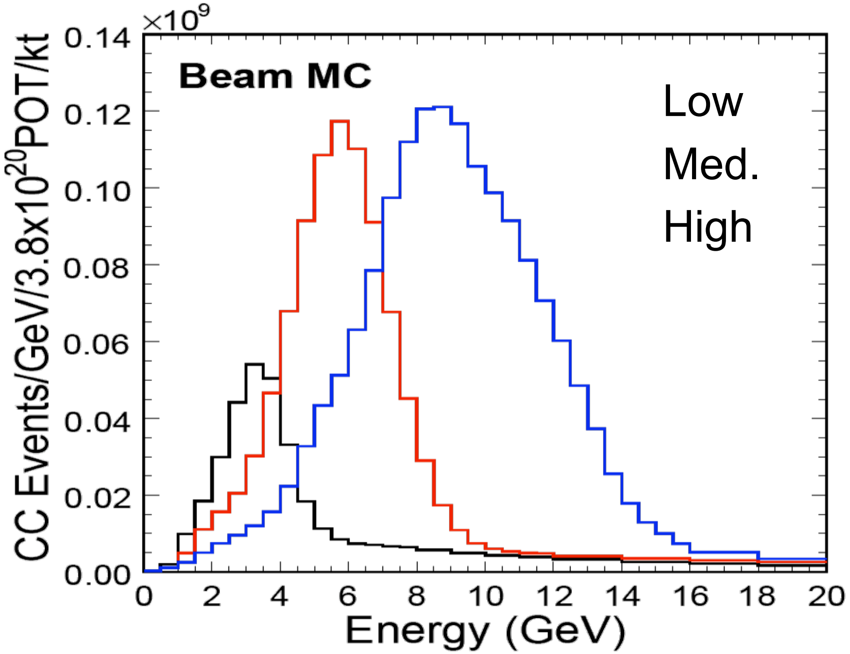
$\Delta m^2_{32} = m_3^2 - m_2^2$

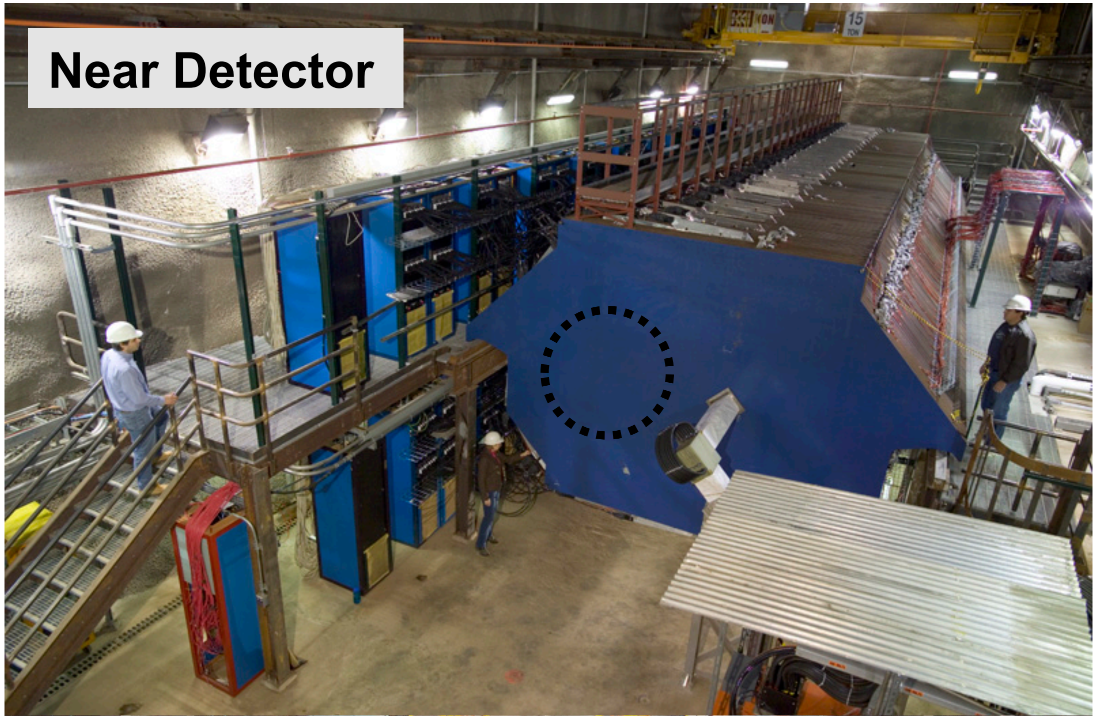


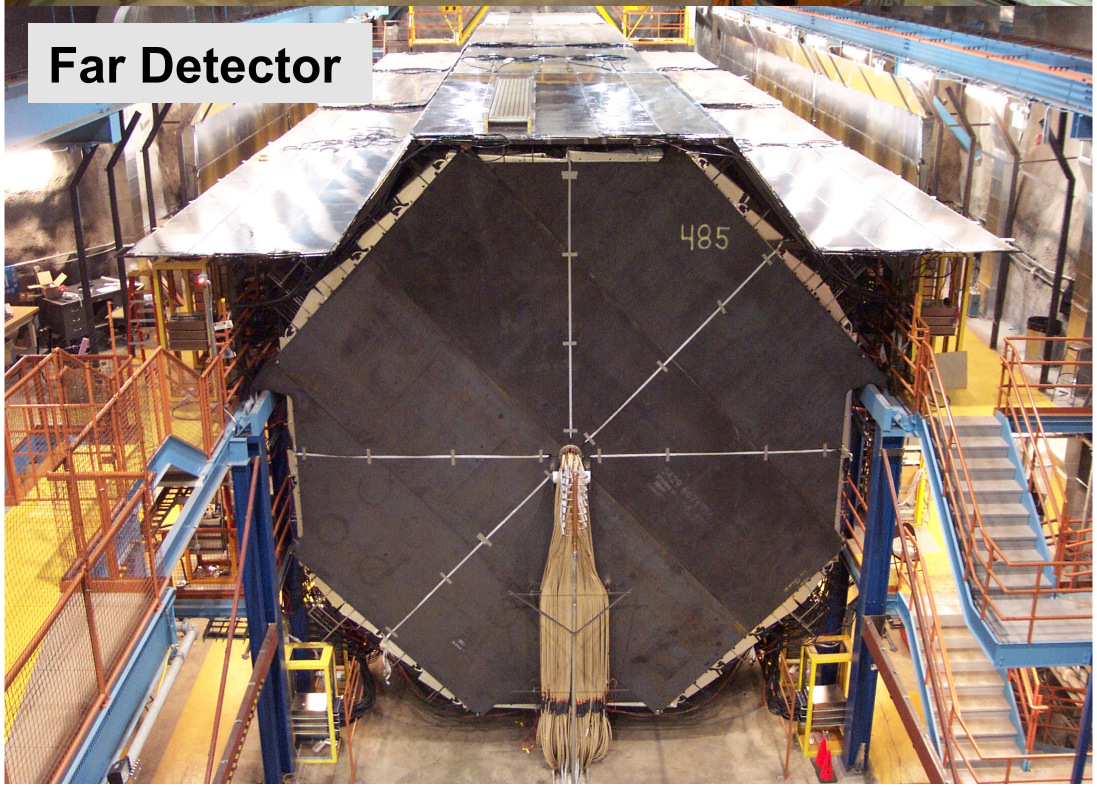
Neutrino Beam (NuMI)



- 120 GeV protons strike target
- 10 μs long pulse of 3×10^{13} protons every 2.2 seconds (275 kW)
- Two magnetic horns focus secondary π/K
    - decay of π/K produce neutrinos
- Variable neutrino beam energy





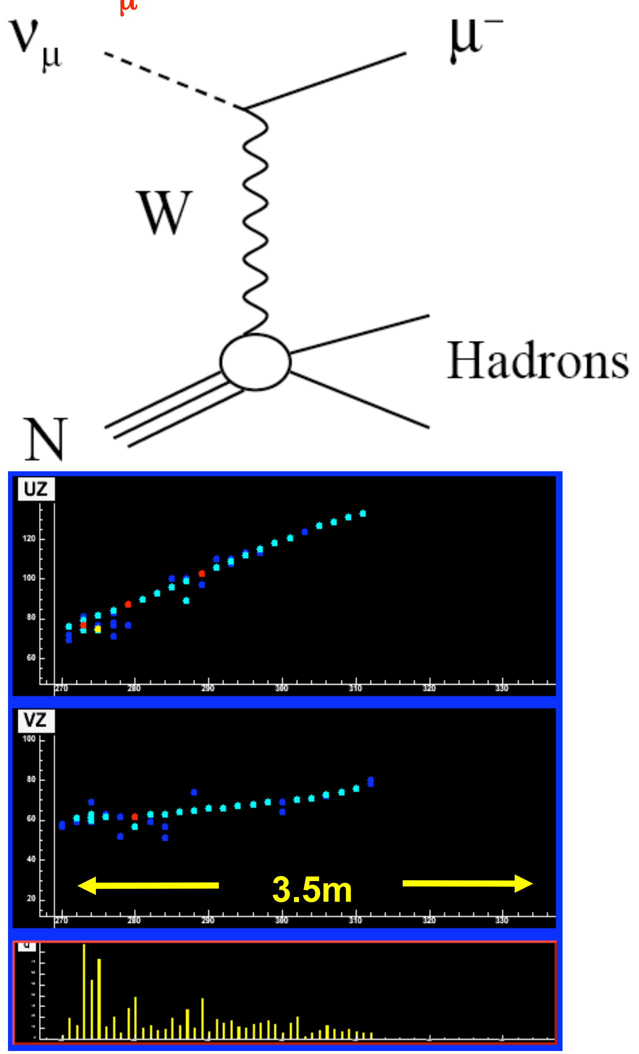


MINOS Detectors

- Massive
  - 1 kt Near detector
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

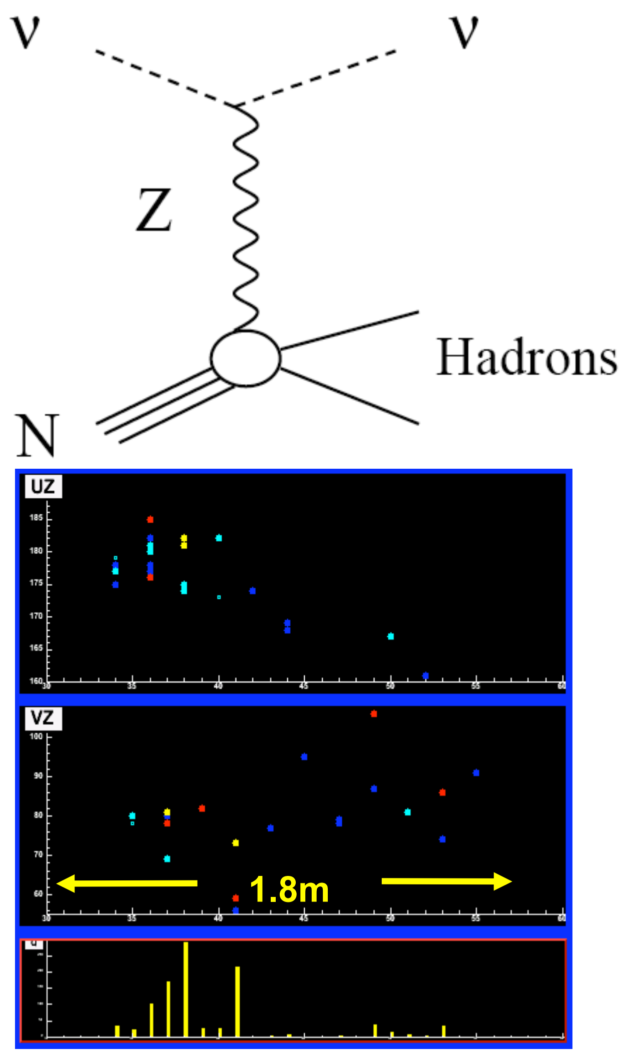
MINOS Event Topologies (MC)

ν_μCC Event



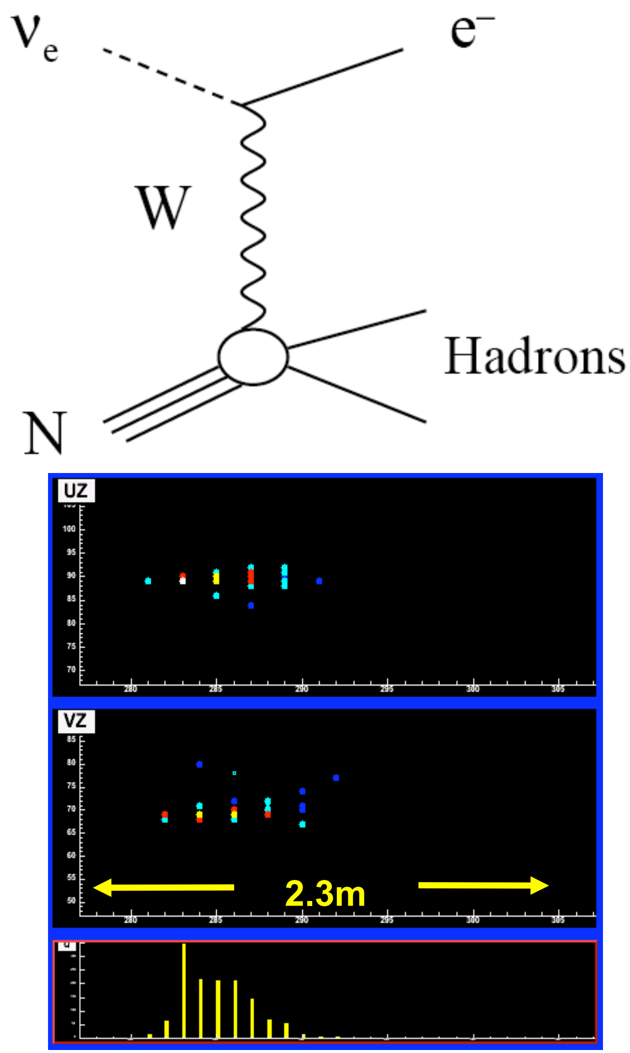
long μ track+ hadronic activity at vertex

NC Event



short event, often diffuse

ν_eCC Event

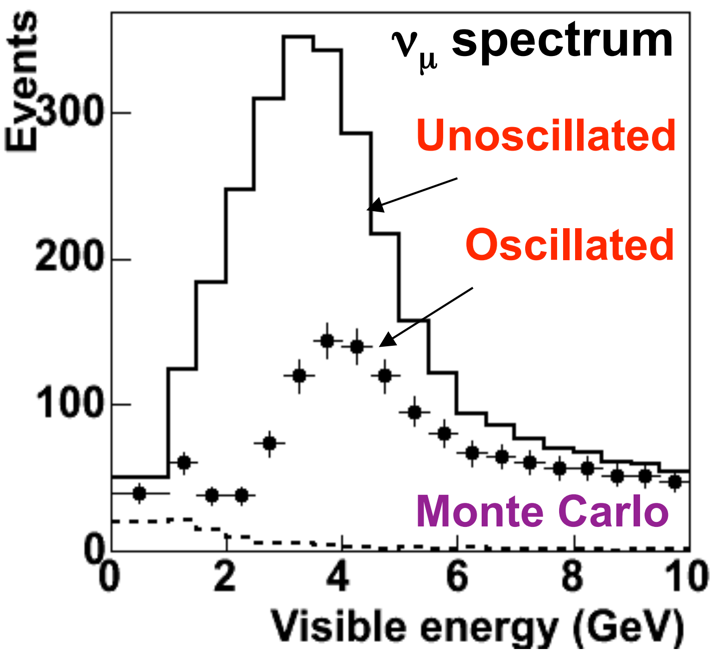


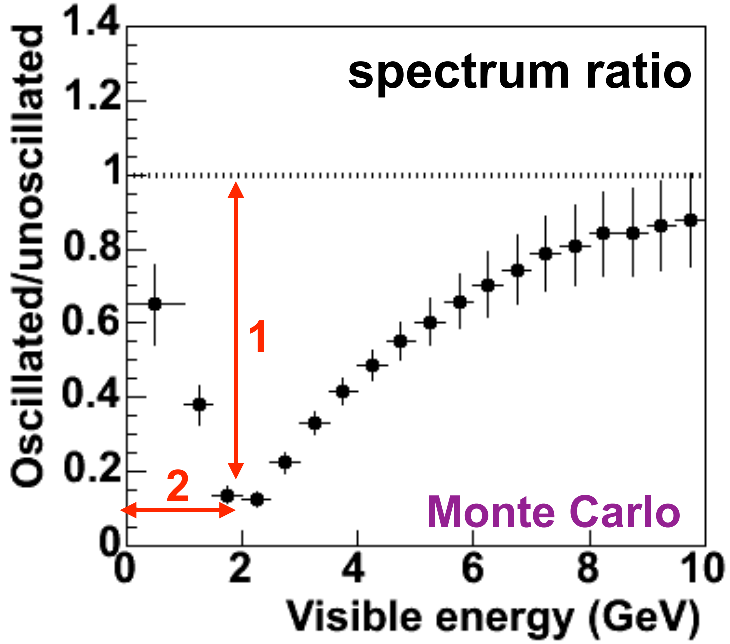
short, with typical EM shower profile

Muon Neutrino Disappearance Analysis

Experimental Approach

- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate using MC
  - Compare to measured spectrum at Far detector



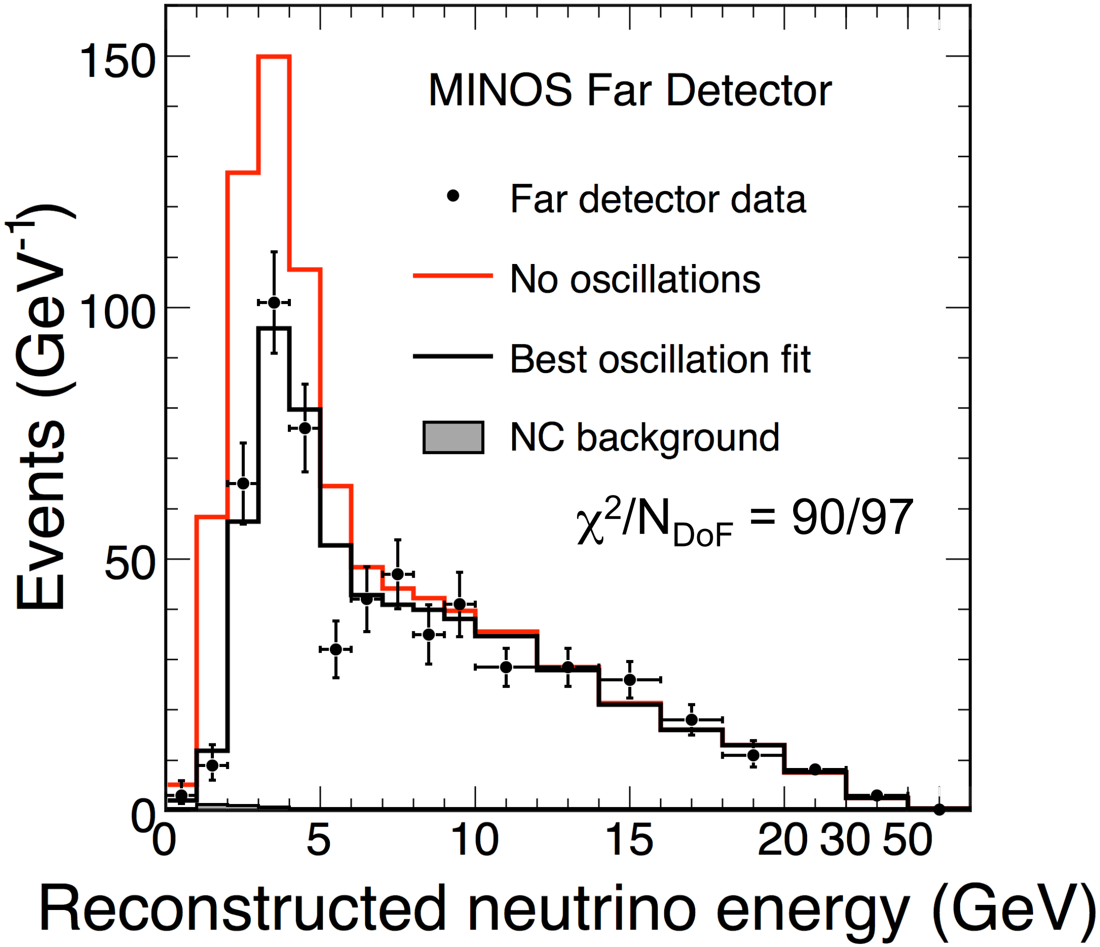


$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\boxed{\sin^2 2\theta}}_{1} \sin^2(1.267 \underbrace{\boxed{\Delta m^2}}_{2} L / E)$$

Far Detector ν_μ CC Data

- See strong energy dependent distortion of spectrum
- Energy spectrum fit with the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Allowed Region

- Fit constrained to physical region and includes 3 largest systematic uncertainties
- Results:

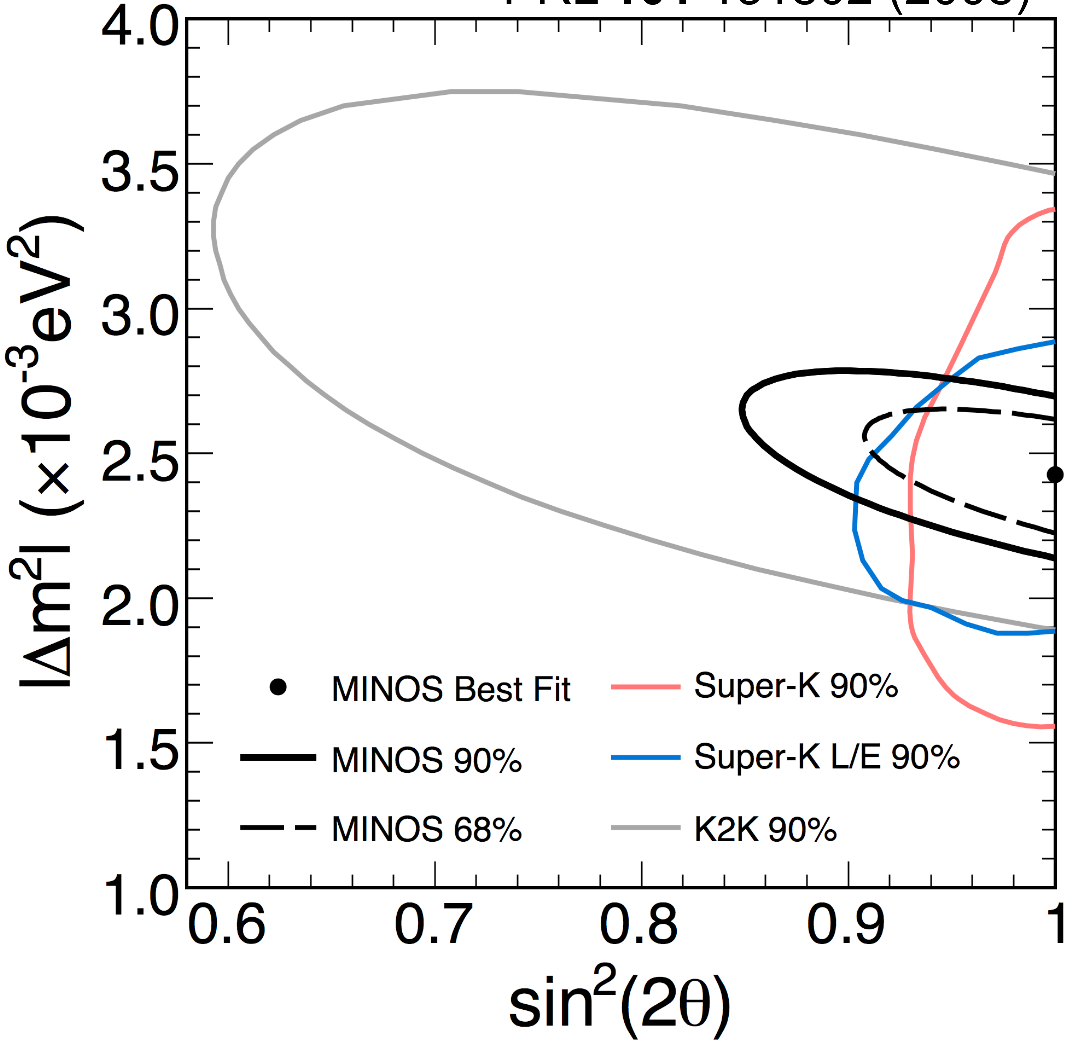
$|\Delta m^2_{32}|=(2.43 \pm 0.13) \times 10^{-3}\ eV^2$

at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$

at 90% C.L.

PRL **101** 131802 (2008)



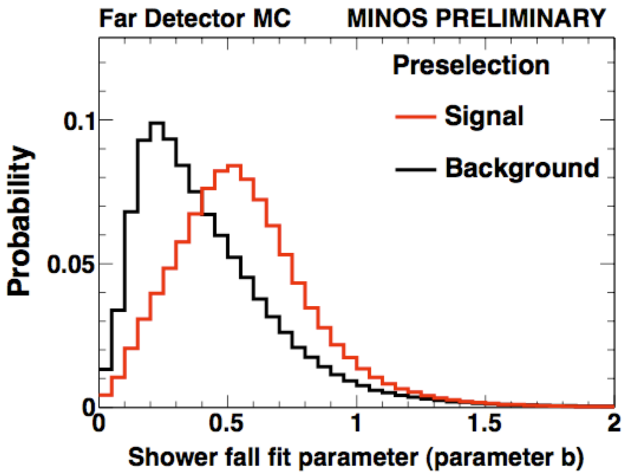
Most precise measurement of $|\Delta m^2_{32}|$ performed to date

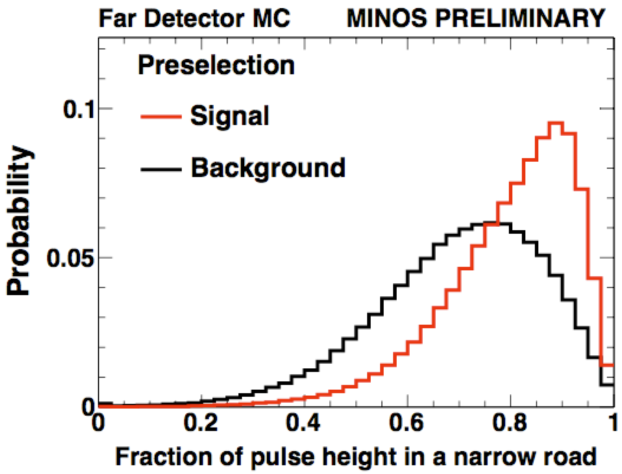
Electron Neutrino Appearance Analysis (new!)

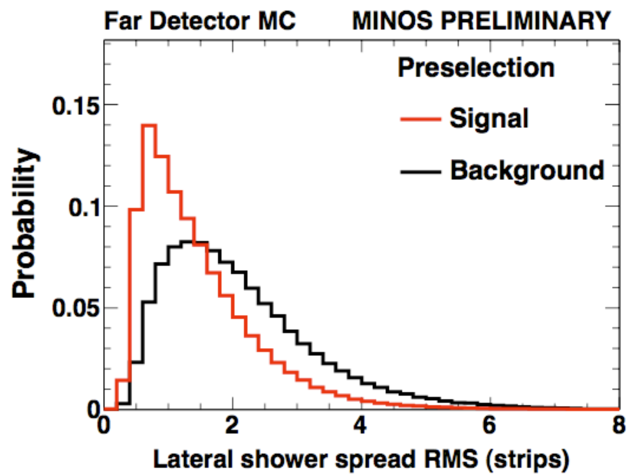
$\nu_\mu \rightarrow \nu_e$ Oscillation Search Overview

- Sub-dominant neutrino oscillations
  - Look for ν_e appearance at Far detector
    - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
      - also CPv and matter effects: not shown here but included in fit
  - Electron neutrino events only 2% of total (at Chooz limit)
- Select events w/ compact shower, typical EM profile
  - MINOS optimised for ν_μ
  - ν_e signal selection is harder
    - Steel thickness 2.5 cm = 1.4 X_0
    - Strip width 4.1cm ~ Molière radius (3.7cm)
- Use the Near detector to determine the background

Selecting ν_e Events

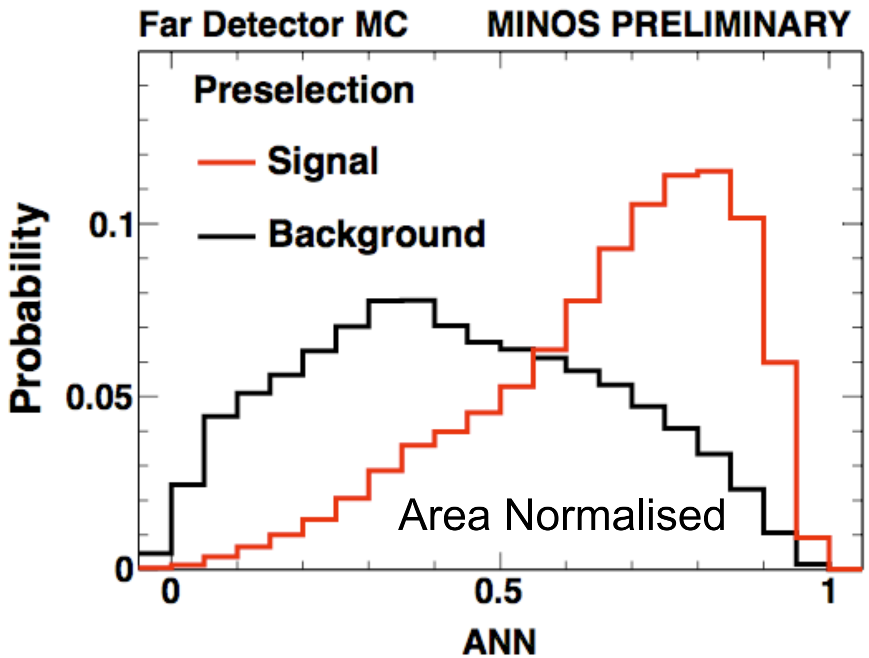




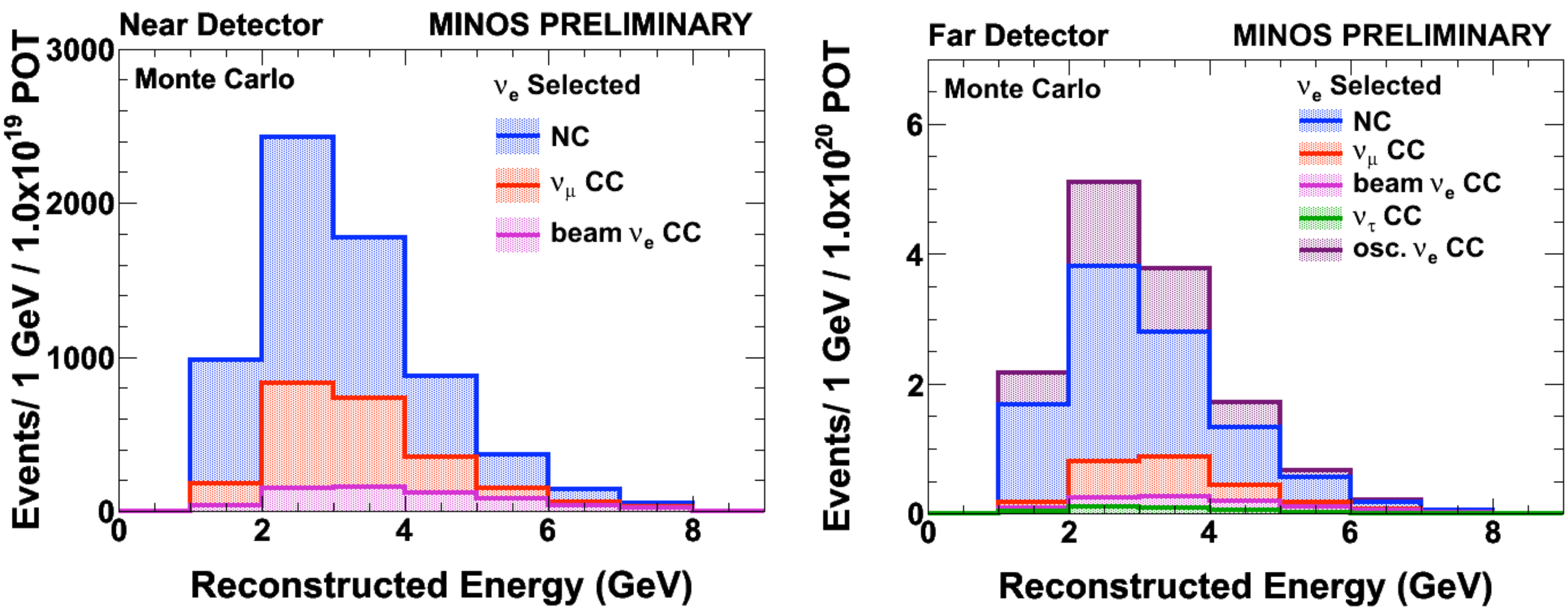


- 11 variables chosen describing length, width and shower shape
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - ν_μCC rejection >99.4%
  - signal/background 1:4

at Chooz limit



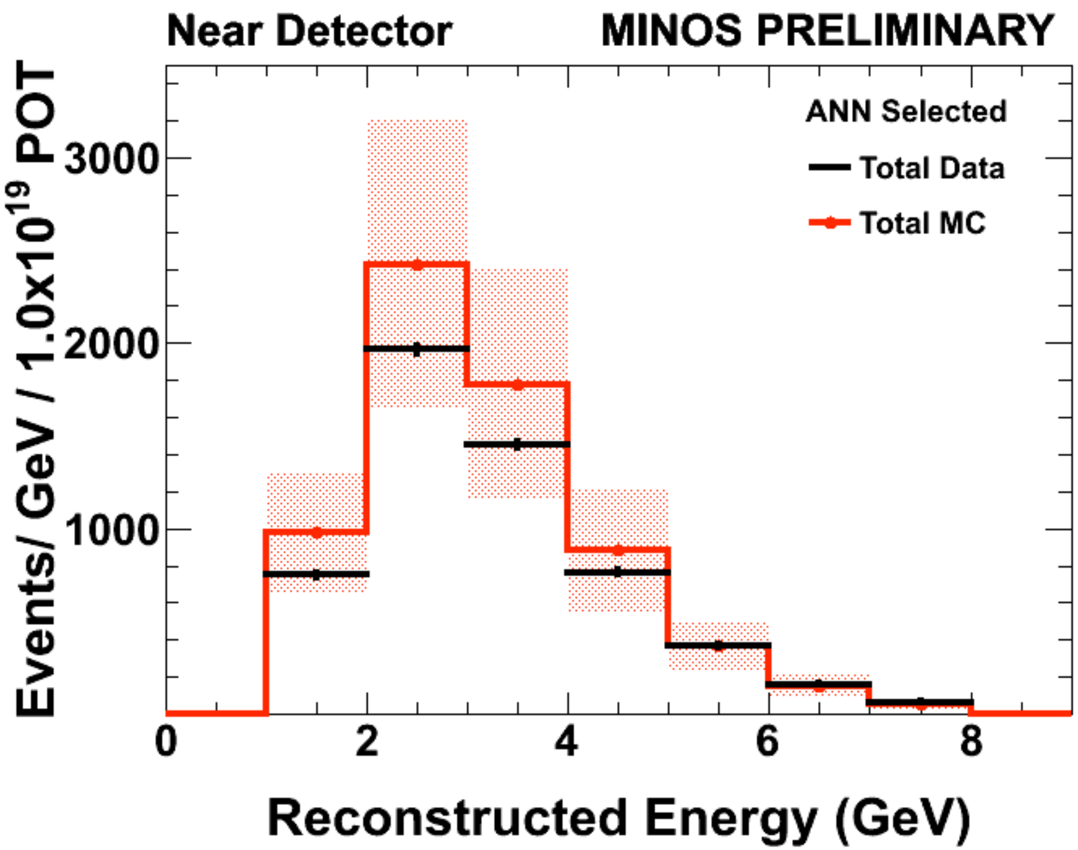
MC Event Composition in 2 Detectors



- Primary background from NC events, also
  - high-y ν_μ CC, beam ν_e, oscillated ν_τ at Far detector
- Right plot: purple shows an appearance signal at the Chooz limit ($\sin^2 2\theta_{13}=0.15$)

Near Detector Data

- *O*(20%) data/MC differences in Near det.
  - not surprising, strong background rejection leaves just tails of distributions
  - such differences are expected from the uncertainties in the MC simulation of the hadronisation model
    - tuned to sparse external data
- Use a data driven technique to measure Near detector background
  - compare horn on/off data
    - fit for CC and NC components



Use measured Near detector background and MC to extrapolate to the Far detector

Preliminary Uncertainties on Background

Preliminary Uncertainties	Size of error
1.) Extrapolation systematic	6.4%
2.) Horn on/off systematic	2.7%
3.) Horn on/off statistical	2.3%
Total (sum in quadrature)	**7.3%**
Statistical error (data)	**19%**

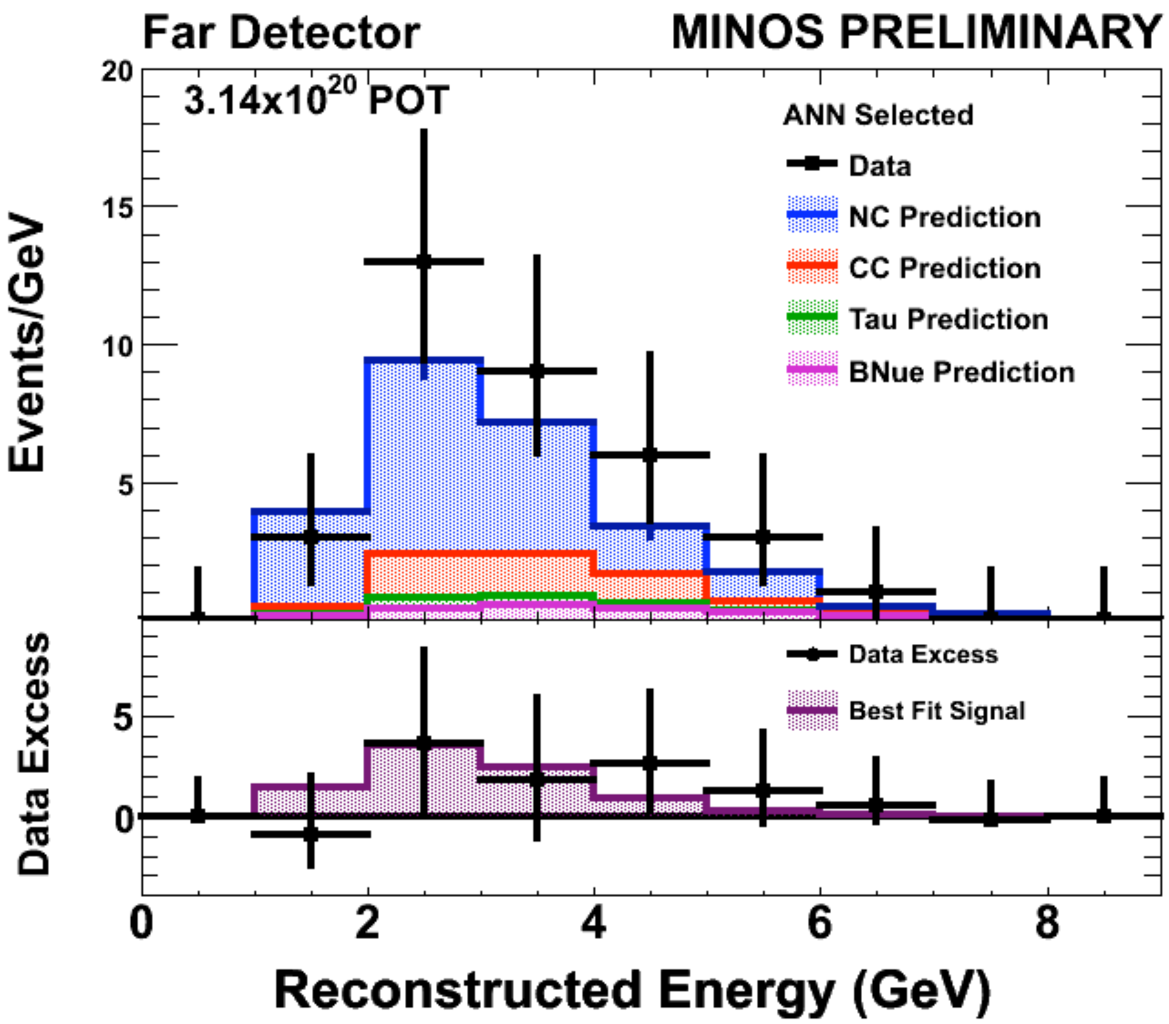
- Statistical error dominates
- Systematic error primarily from extrapolating Near detector measurement of background to Far detector

Far Detector Energy Spectrum

- A blind analysis was performed:
  - all procedures for calculating background and signal were finalised before the Far detector data were looked at
- Expected background:

  27 ± 5(stat) ± 2(sys)
- Observed events:

  35
- A 1.5σ excess over background prediction



Fit the data to the oscillation hypothesis, obtain the signal prediction for the best fit point

Allowed Region

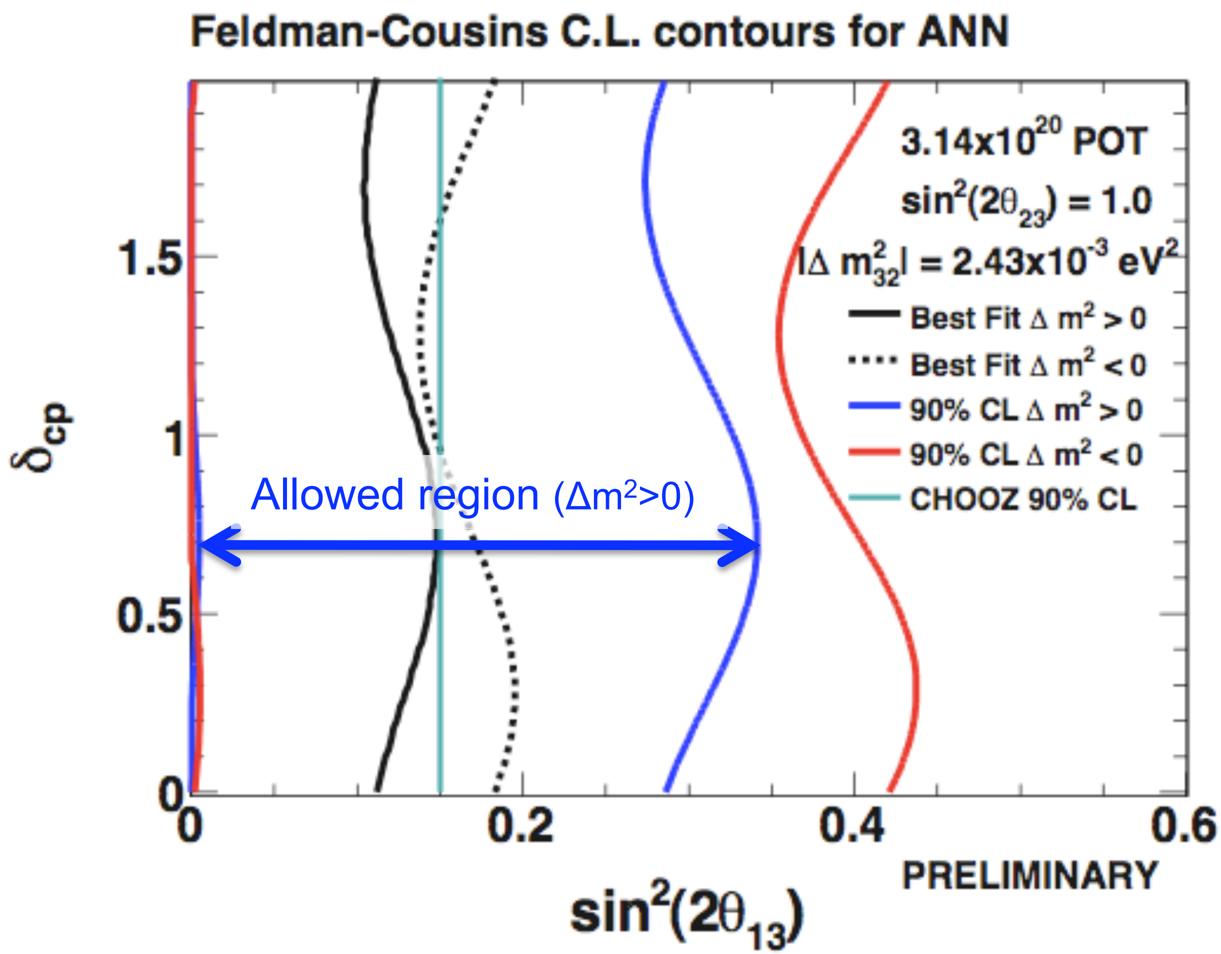
- A Feldman-Cousins method was used
- Fit simply to the number of events from 1-8 GeV
- Best fit and 90% C.L. limits are shown:
  - for both mass hierarchies
  - at MINOS best fit value for Δm^2_{32} & $\sin^2(2\theta_{23})$
- Results:

Normal hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)

Inverted hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.42$ (90% C.L.)



Interpretation

- A 1.5 sigma excess is well within the realms of a statistical fluctuation
- Future ν_e appearance analysis:
  - will update MC and reconstruction
  - more than double statistics (already have x2 data!)
  - other analysis improvements too
  - aim to release 2^{nd} result a year from now
- Watch this space!

Neutral Current Analysis

- Looking for sterile neutrino mixing -

Neutral Current Analysis

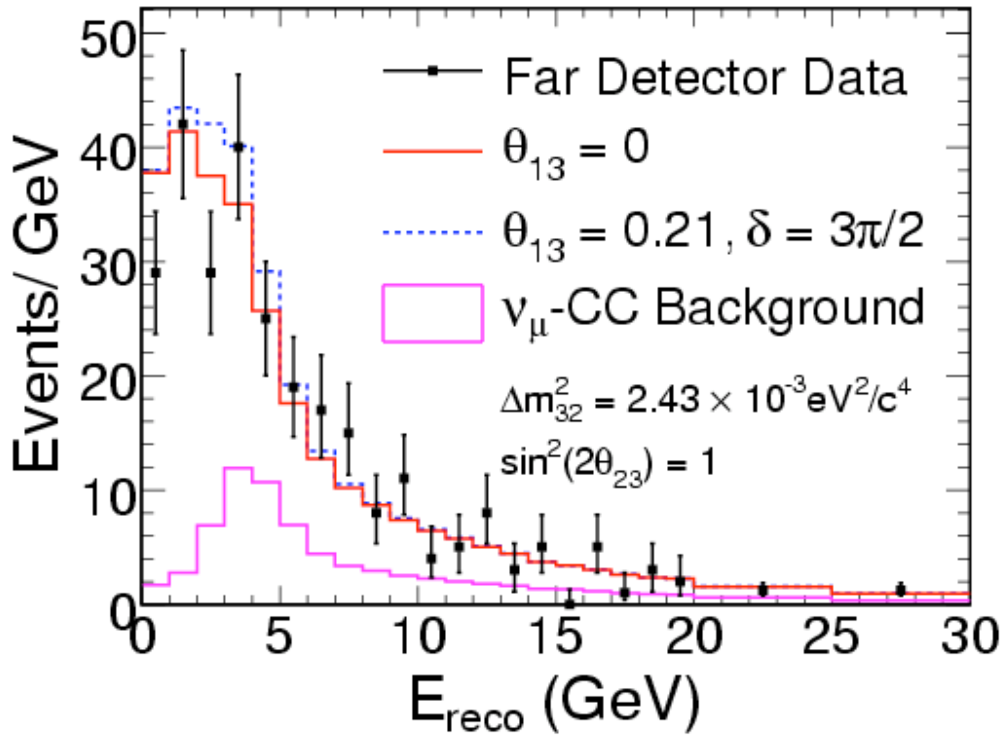
- General NC analysis overview:
  - All active neutrino flavours participate in NC interaction
  - Mixing to a sterile-ν will cause a deficit of NC events in Far Det.
  - Assume one sterile neutrino and that mixing between ν_μ, ν_s and ν_τ occurs at a single Δm^2
- Survival and sterile oscillation probabilities become:

$$P(\nu_\mu - \nu_\mu) = 1 - \alpha_\mu \sin^2(1.27 \Delta m^2 L / E)$$

$$P(\nu_\mu - \nu_s) = \alpha_s \sin^2(1.27 \Delta m^2 L / E)$$

($\alpha_{\mu,s}$ = mixing fractions)

PRL **101** 221804 (2008)



Simultaneous fit to CC and NC energy spectra yields the fraction of ν_μ that oscillate to ν_s:

$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} = 0.28^{+0.25}_{-0.28}(\text{stat.+syst.})$$

$$\boxed{f_s < 0.68 \quad (90\%\ \text{C.L.})}$$

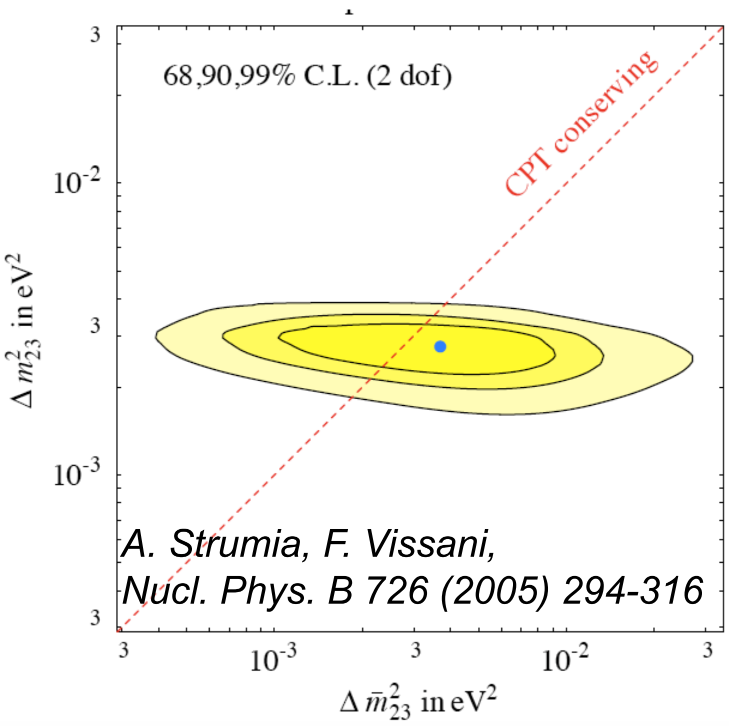
Future plans

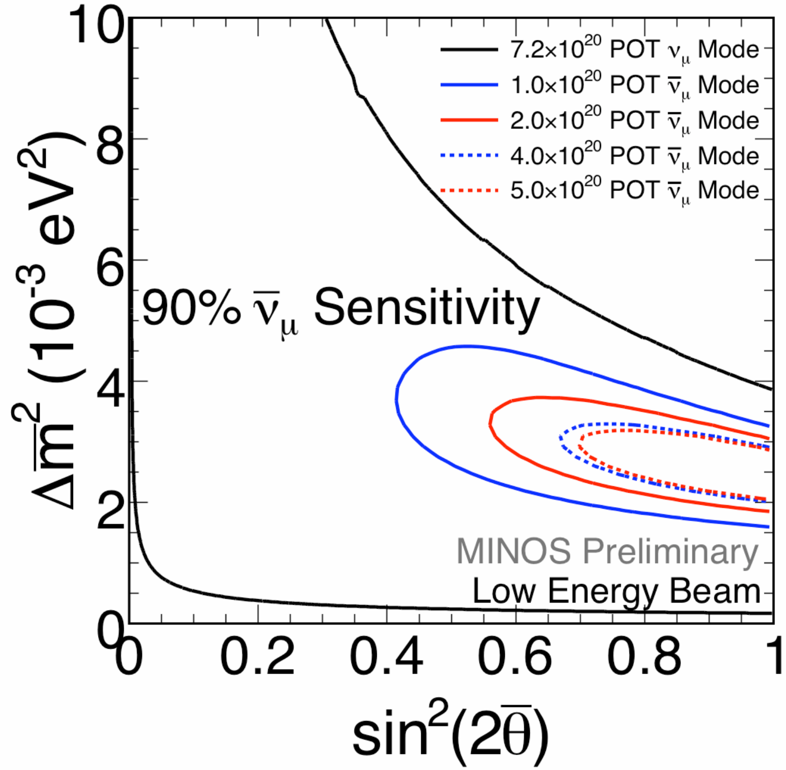
a.) Update all analyses with more than double the data set

b.) Muon antineutrino possibilities

Muon Anti-neutrino Running

- Neutrino Δm^2_{32} measurement will reach the point of diminishing returns after next result (without accelerator/beam upgrade)
- Possibility to switch beam magnetic horns to focus π^-
  - create a muon anti-neutrino beam
  - MINOS can make the first direct measurement
    - rapidly reduce the uncertainty on $\Delta\overline{m}^2_{32}$ by an order of magnitude



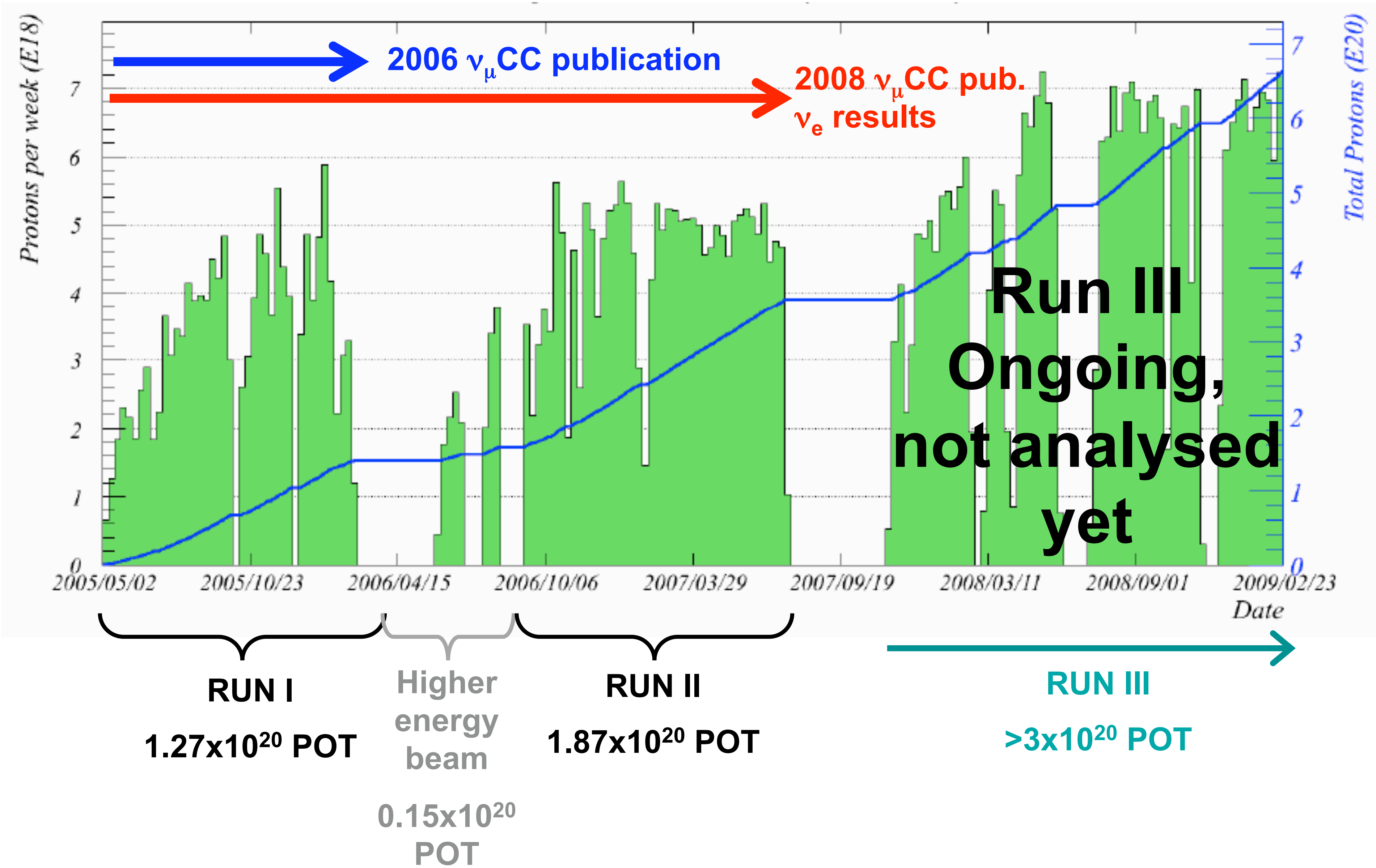


Conclusions

- MINOS has analysed 3.2×10^{20} POT of beam data (>6.6×10^{20} POT data now taken)
- Search for electron neutrino appearance
  - 1.5 σ excess over background prediction
  - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.) (for normal mass hierarchy, $\delta_{CP}=0$)
- Muon neutrino disappearance
  - $|\Delta m^2_{32}| = (2.43\pm0.13)\times10^{-3}\ \mathrm{eV}^2$ (68% C.L.)
  - $\sin^2(2\theta_{23}) > 0.90$ (90% C.L.)
- Search for sterile neutrino mixing fraction
  - $f_s < 0.68$ (90% C.L.)
- Muon antineutrino run possibility

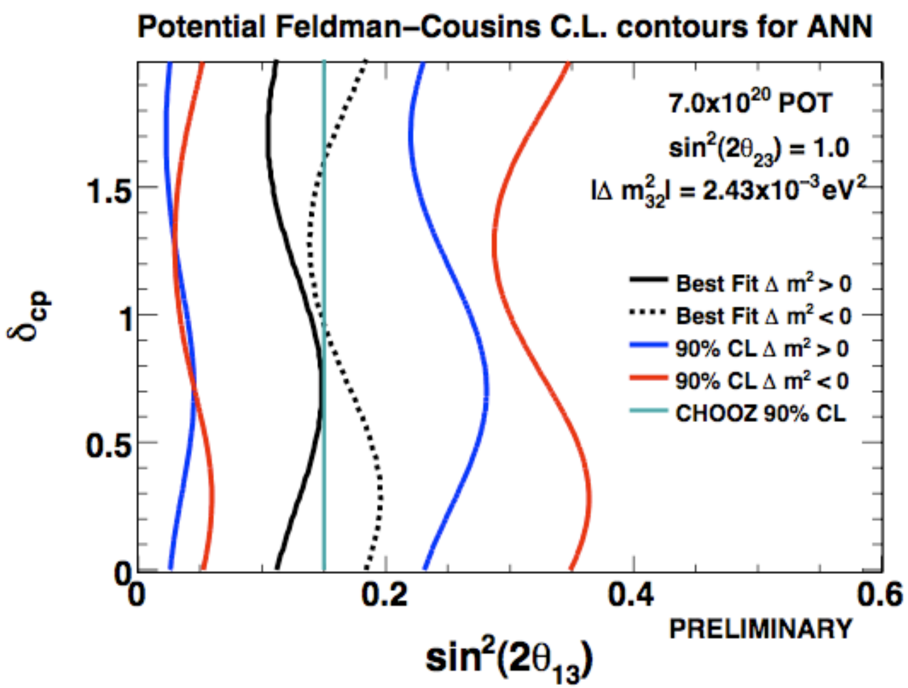
Backup slides

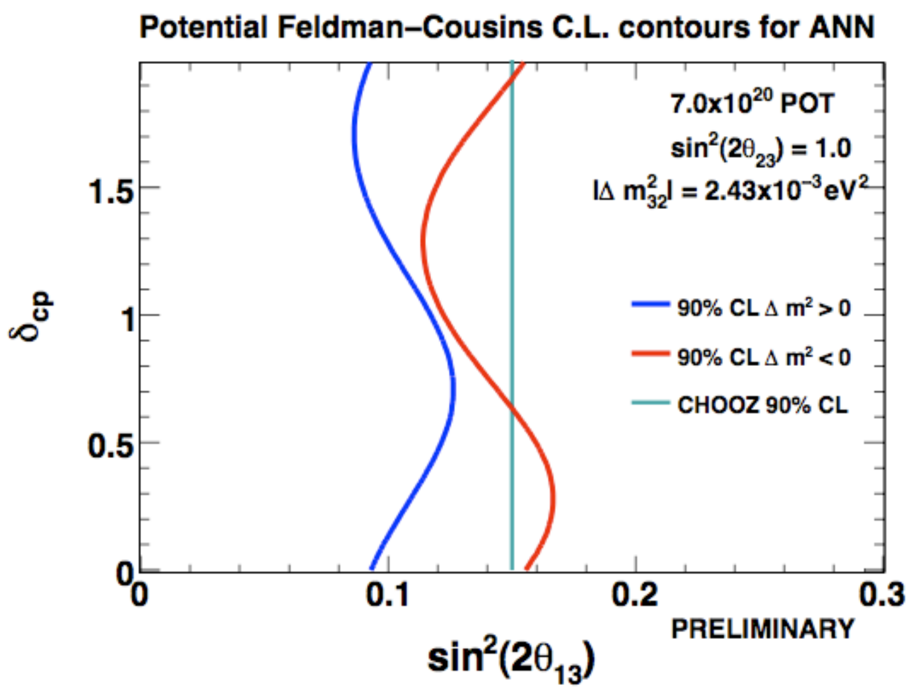
Accumulated Beam Data



Future 90% CL contours

7.0 x10^{20} POT





Future measurement if data excess persists.

Future limit if excess cancels with more data.

We are close to doubling the data in current running!

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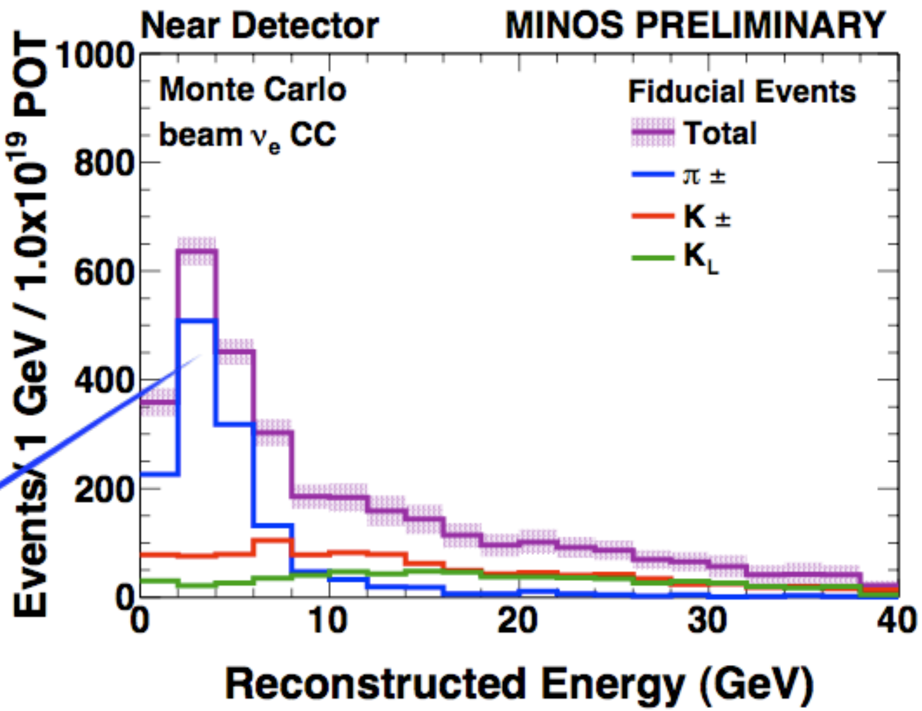
Beam ν_e component

- Neutrino beam has 1.3% of ν_e contamination from pion and kaon decays.

- Region of interest for the ν_e oscillation analysis, 1-8GeV, dominated by events from secondary muon decays:

- $$\begin{aligned}\pi^+ &\rightarrow \mu^+\nu_\mu \\ &\quad \hookrightarrow e^+\bar{\nu}_\mu\nu_e\end{aligned}$$

- Near and Far beam ν_e spectra are constrained by using ν_μ events from several beam configurations.



- Uncertainties on the flux in the region of interest are ~10%.

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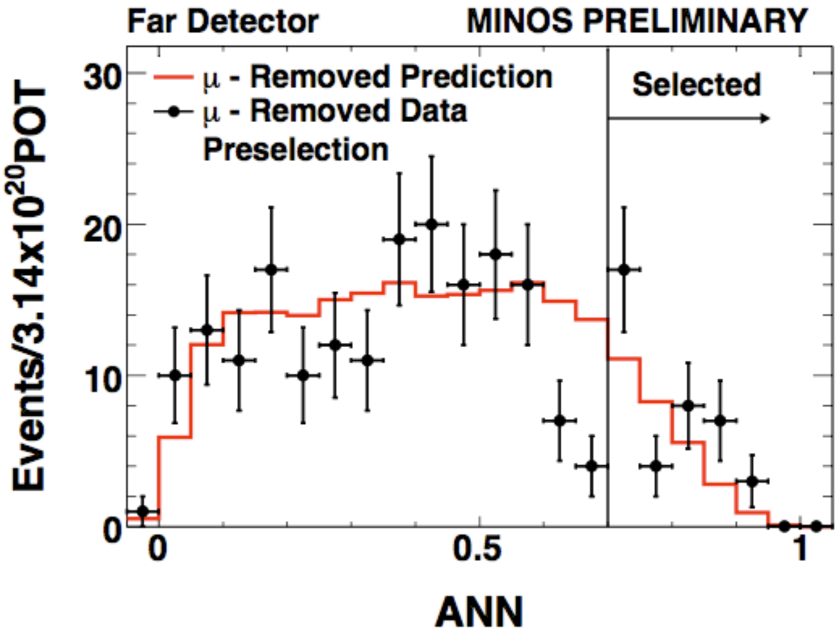
Sidebands

Muon removed sideband



- **We observe a total of 39 events.**
- **We expect 29±5(stat)±2(sys) events.**

- Result is within 2 σ
- It is possible this is a statistical fluctuation or it might hint at an unexplained Far/Near difference.

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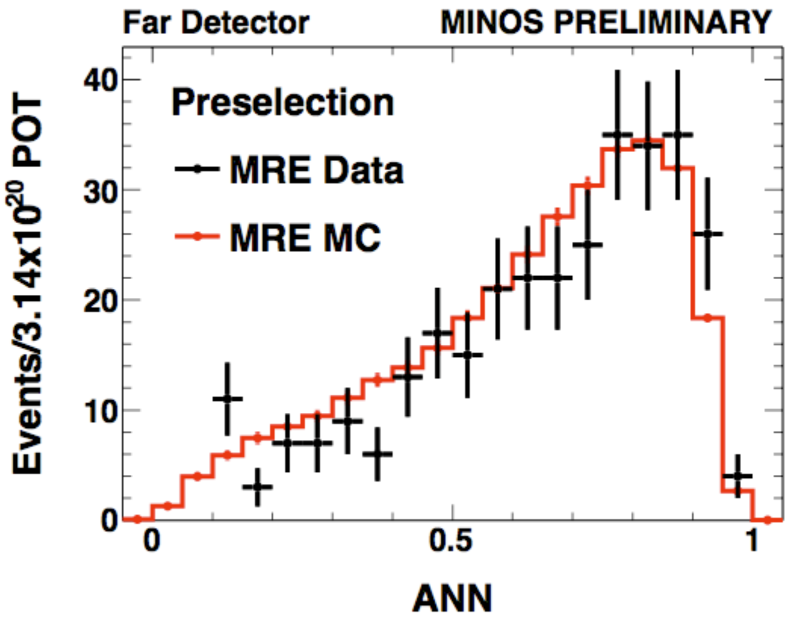
Muon removed w/electron sideband

- Adding the electron to the muon removed events, present good agreement in PID.

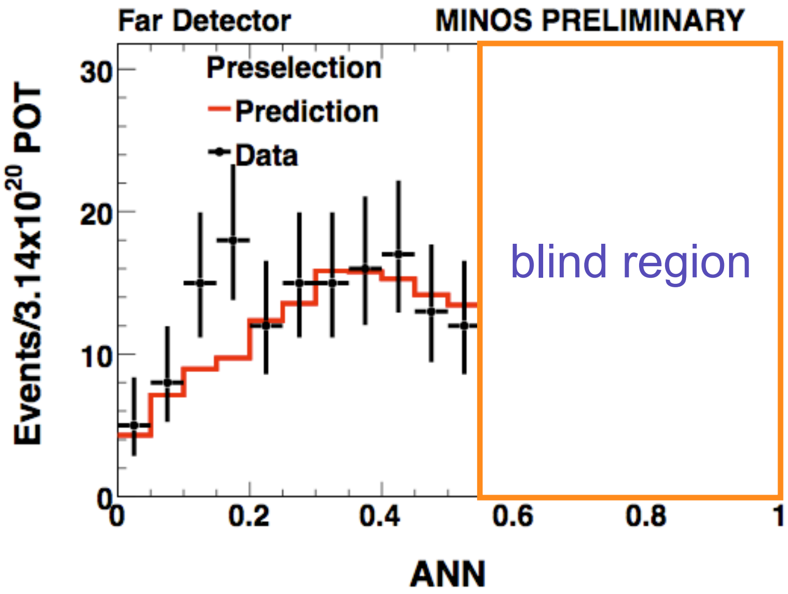


- **We observe a total of 159 events.**
- **We expect 152±13(stat)±12(sys) events.**

Result is within 0.5 σ

Lower PID region

- We also looked in the lower PID region. Finding no obvious disagreement.



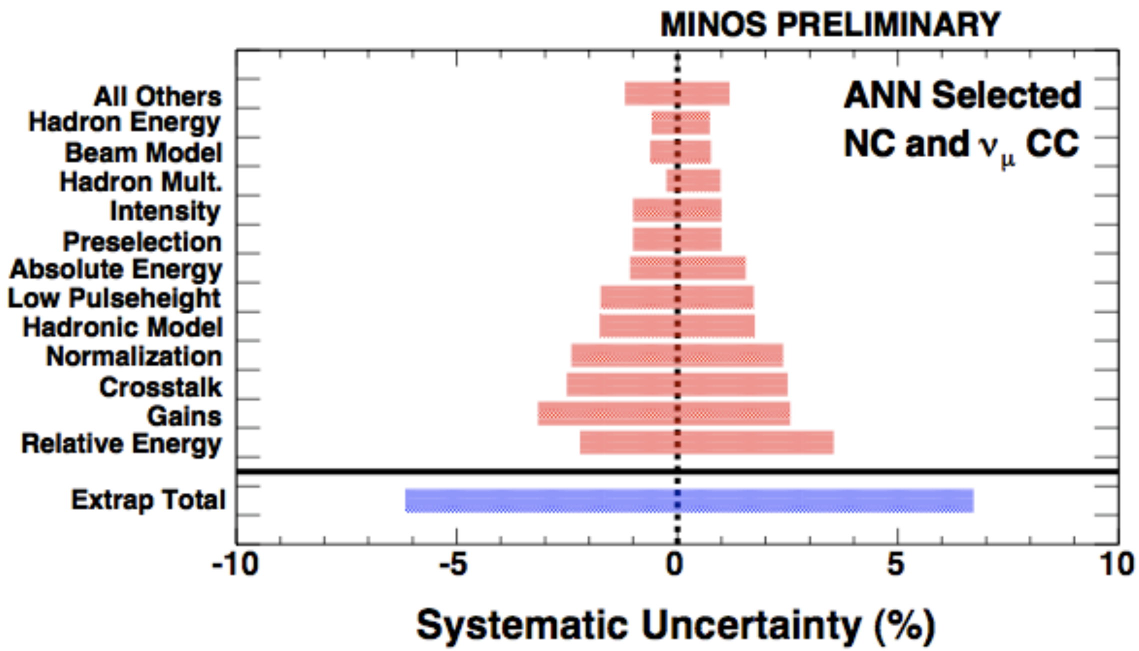
- **We observe a total of 146 events.**
- **We expect 132±12(stat)±8(sys) events.**

Result is ~1σ above expectation

Systematic Errors

FD background systematic errors

Extrapolation errors

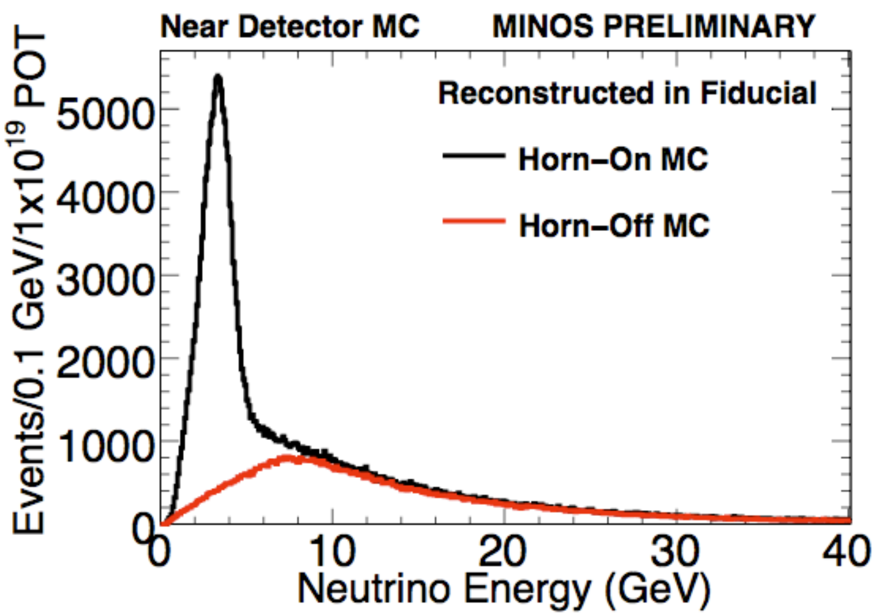


- For most systematic errors, we generated special MC with the modified parameter in Near and Far. Used this modified MC for extrapolation and calculated the difference with the standard results.
- For the main background components the larger systematics are **relative energy, gains, crosstalk and relative normalization**.

Horn on/off

Estimating the background using horn on and horn off data

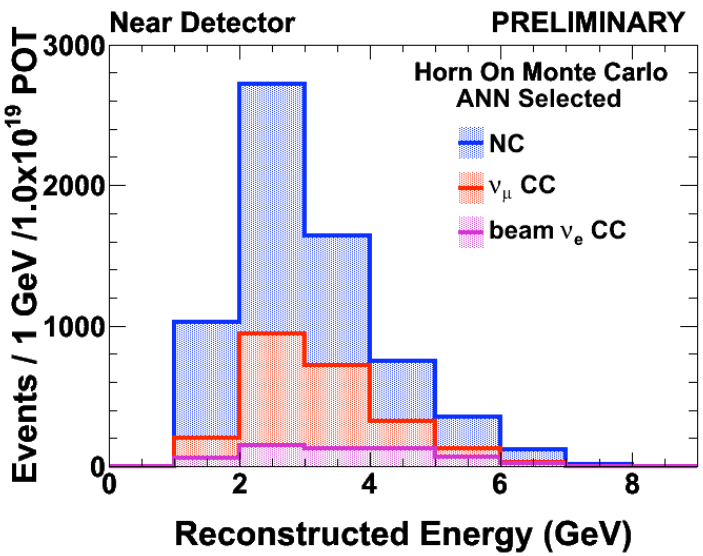
- When beam horns are turned off, the parent pions do not get focused, resulting in the disappearance of the low energy peak in the neutrino energy spectrum.

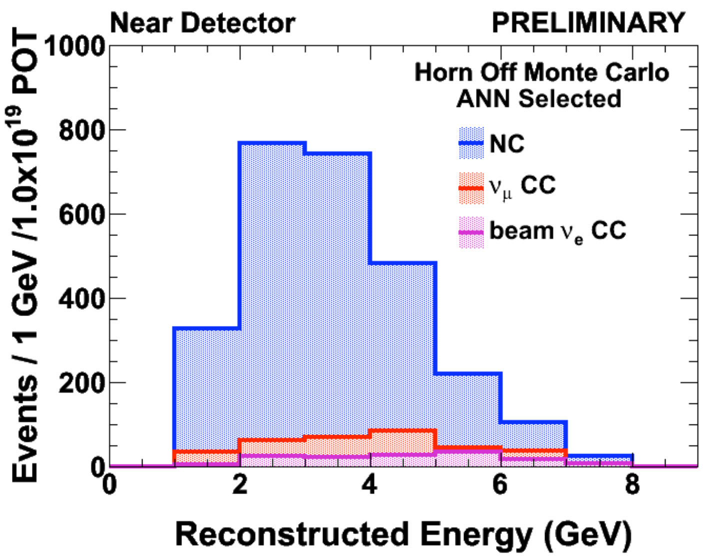


- The consequence is a spectrum dominated by NC arising from the long tail in true neutrino energy that gets measured in our region of interest in visible energy.

Estimating the background using horn on and horn off data

- After applying the ν_e selection cuts to the ND data, the composition of the selected events is thus very different with the NuMI horns on or off.





- Using the horn off spectrum which is dominated by NC, we can measure that component with better precision than in the horn on beam.

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Estimating the background using horn on and horn off data

- The **beam ν_e flux** is obtained from the ν_μ CC flux which is constrained by data in the different beam configurations.
- The two main background components can be estimated using the number of data events in the horn on and horn off configurations: $\mathbf{N^{on}}$ and $\mathbf{N^{off}}$.

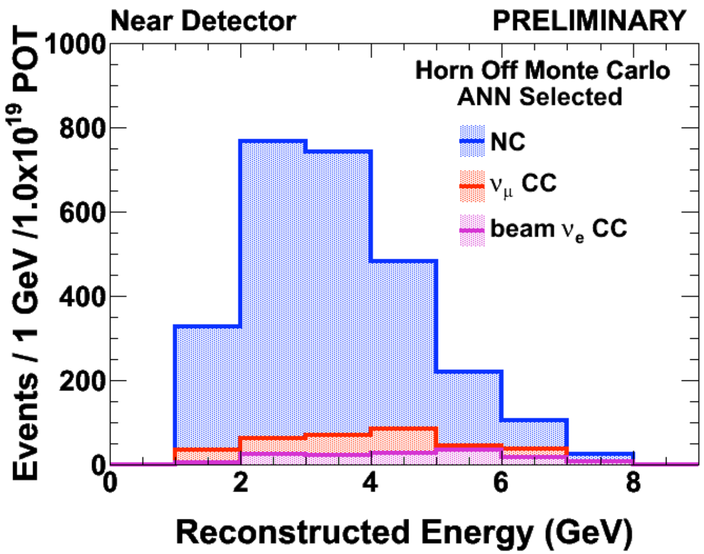
$$\mathbf{N^{on}} = \mathbf{N_{NC}} + \mathbf{N_{CC}} + N_e \qquad (1)$$

$$\mathbf{N^{off}} = r_{NC} * \mathbf{N_{NC}} + r_{CC} * \mathbf{N_{CC}} + r_e * N_e \qquad (2)$$

from MC:

$$r_{NC(CC,e)} = N_{NC(CC,e)}^{off} / N_{NC(CC,e)}$$

The key is to use the **Horn off/on ratios** for each component to solve:



- Producing **data-driven predictions** for NC and ν_μ CC background for the horn on configuration.

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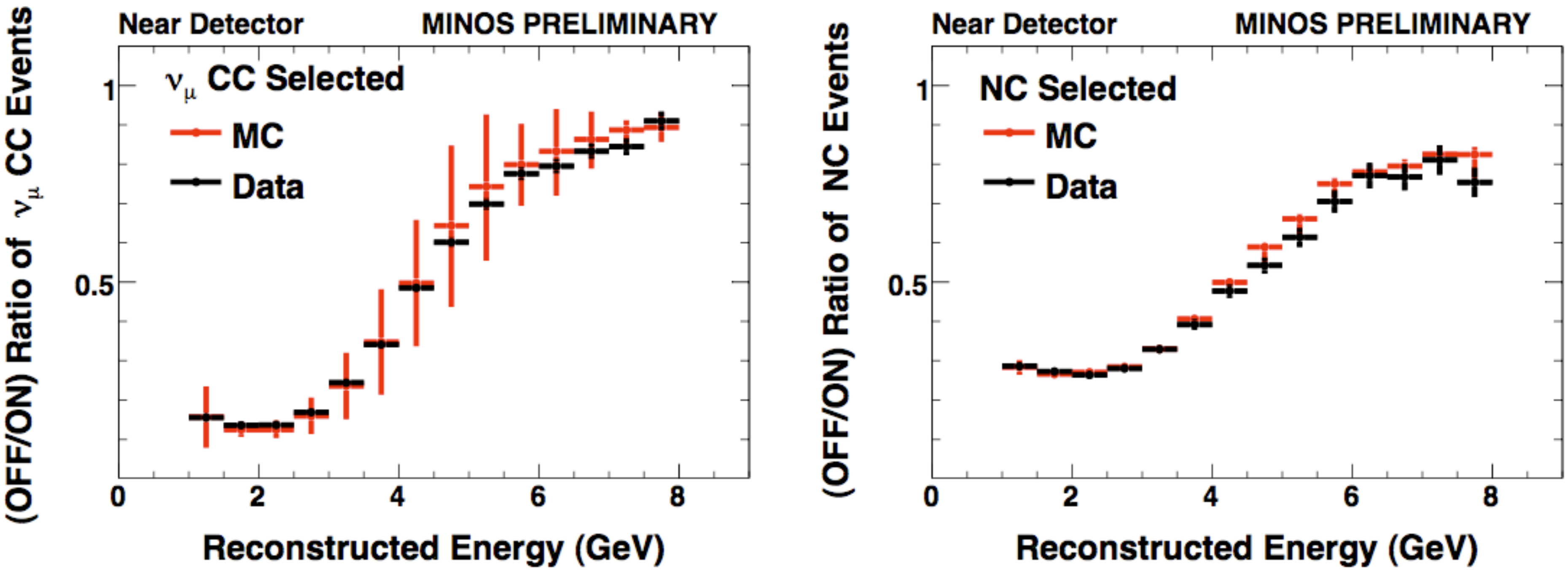
Estimating the background using horn on and horn off data

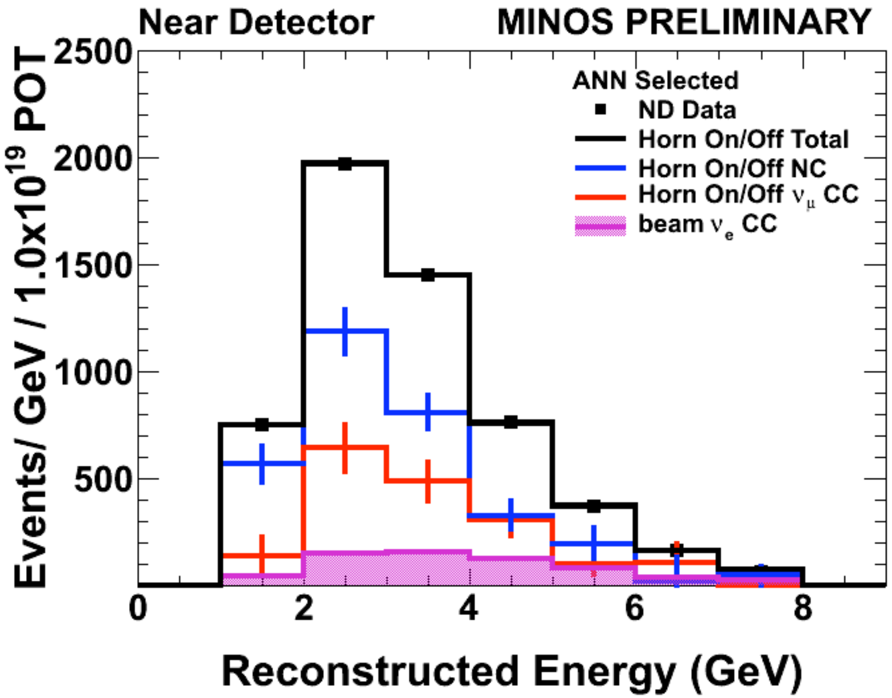
- Horn off/on ratios for ν_μ CC and NC selected events match well between data and MC after fiducial volume cuts.
- Similar ratios are used to solve the horn on/off equations.



MC error statistical plus systematic.

ND data-driven background

Results from the Horn on/off method



- The NC and ν_μ CC components for the the standard beam configuration are simultaneously solved in the horn on/off method and are by definition equal to the data after beam ν_e subtraction.

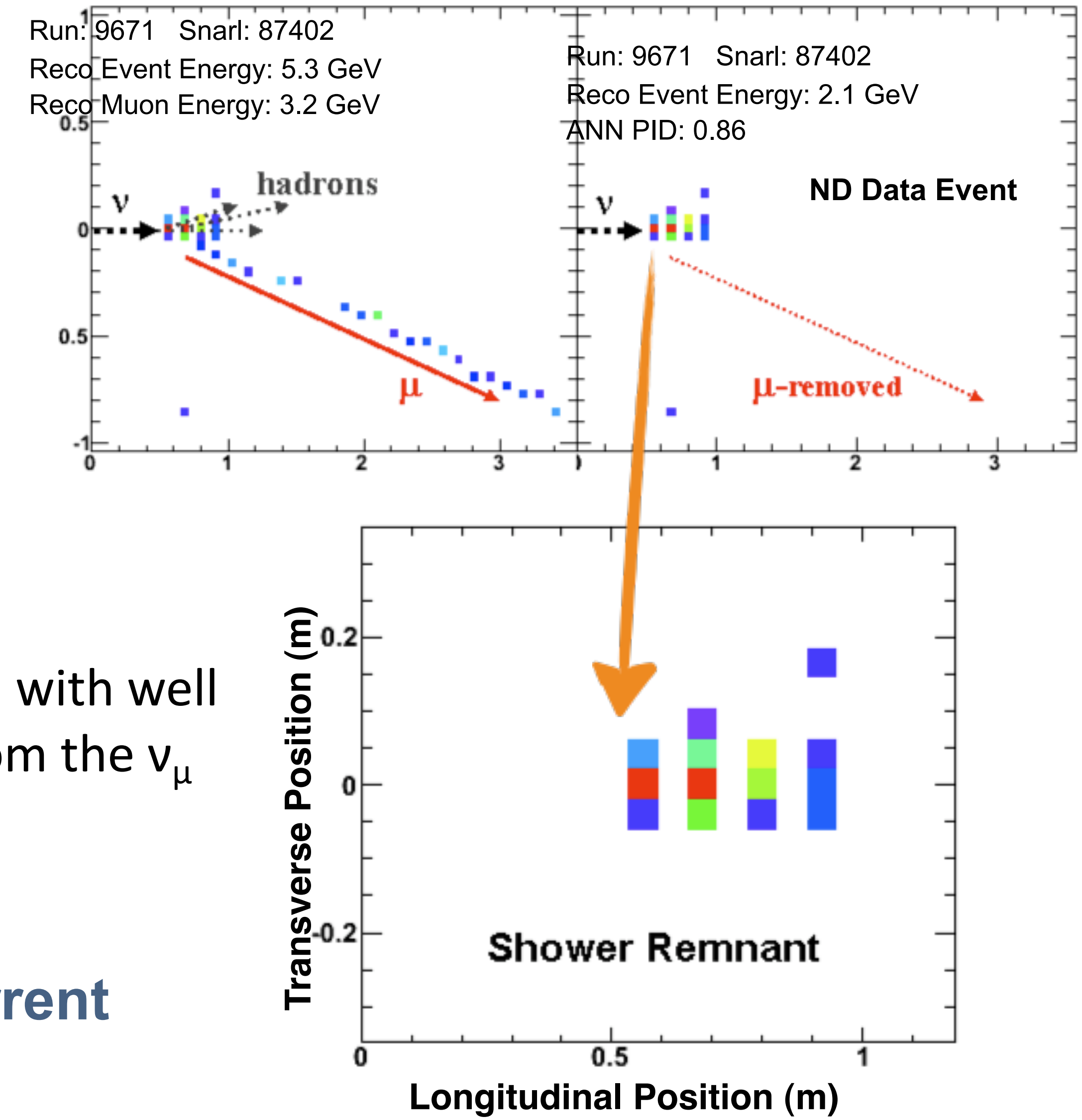
MRCC

Studying hadronic showers using muon removal technique

- Remove the muon track in a selected ν_μ CC event and use the rest as a hadronic shower only event.

- We use events that pass our ν_μ Charged Current event selection, i.e. that have a well defined track.

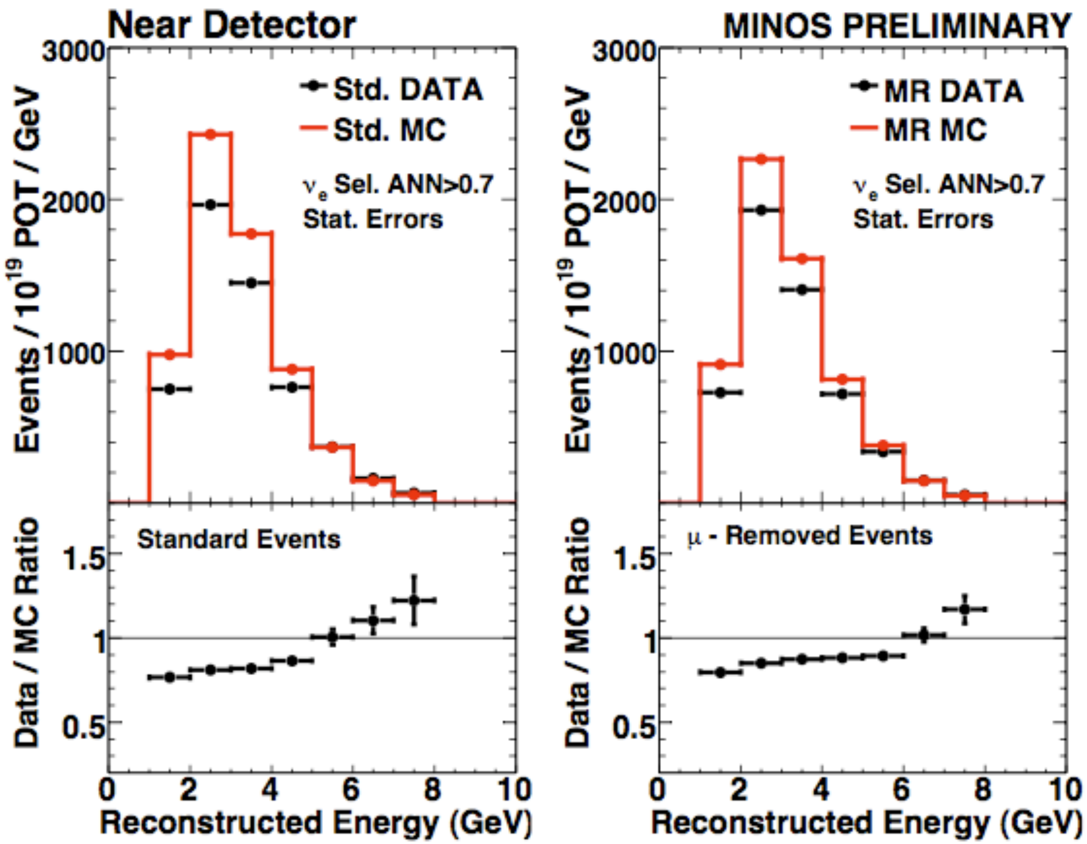
- Well understood ν_μ CC spectra, with well known efficiency and purity from the ν_μ disappearance analysis.



Muon Removed Charged Current events ⇒ MRCC events

Hadronic shower modeling in the ν_e selected data and muon-removed data

- We apply the ν_e selection to the standard data and MC as well as to the Muon Removed data and MC.
- Discrepancy with the model shows the same trend not only in energy but in shower topology for both sets.
- Thus modeling of the hadronic shower is a major contribution to the disagreement.
- As the MRCC sample is independent, we can use it to obtain a **data-driven correction** to the model.



Overall disagreement:

- 16.6% data/MC
- 13.8% MR data/MC

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Hadronic shower modeling in the ν_e selected data and muon-removed data

- We apply the ν_e selection to the standard data and MC as well as to the Muon Removed data and MC.
- Discrepancy with the model shows the same trend not only in energy but in shower topology for both sets.
- Thus modeling of the hadronic shower is a major contribution to the disagreement.
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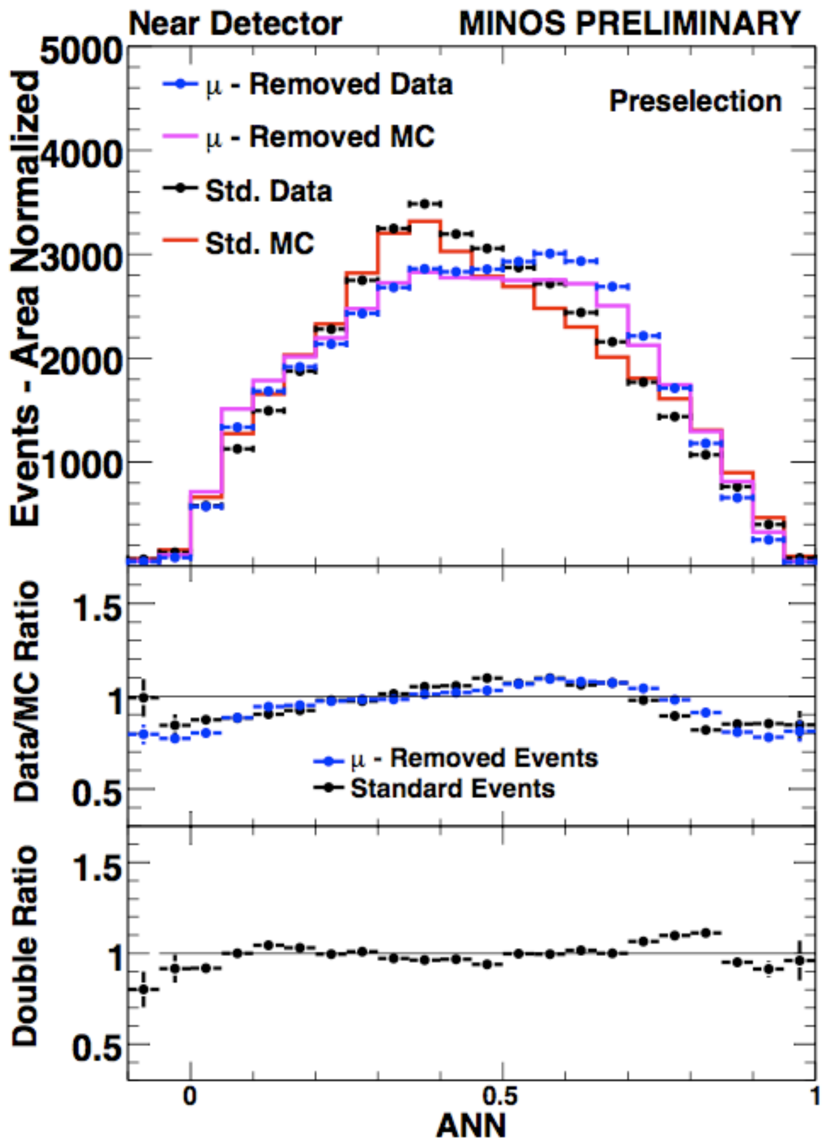


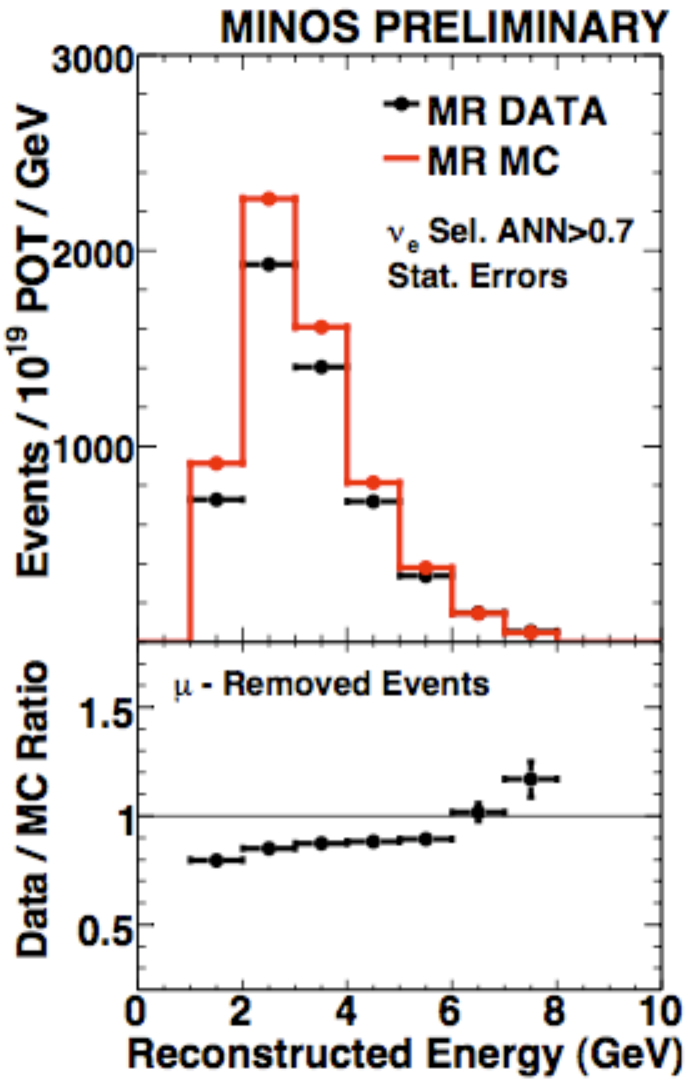
Using MRCC as a data-driven correction

- We use the data/MC ratio from MRCC to obtain a **data-driven correction** that is applied to the standard NC events as a function of energy.

$$NC_i^{corr} = \frac{MRCC_i^{data}}{MRCC_i^{MC}} \times NC_i^{MC}$$

- The number of ν_μ CC events is taken from the number of events in the data minus the corrected NC and beam ν_e events.

- Differences between NC and MRCC showers introduces a systematic error that is difficult to quantify.

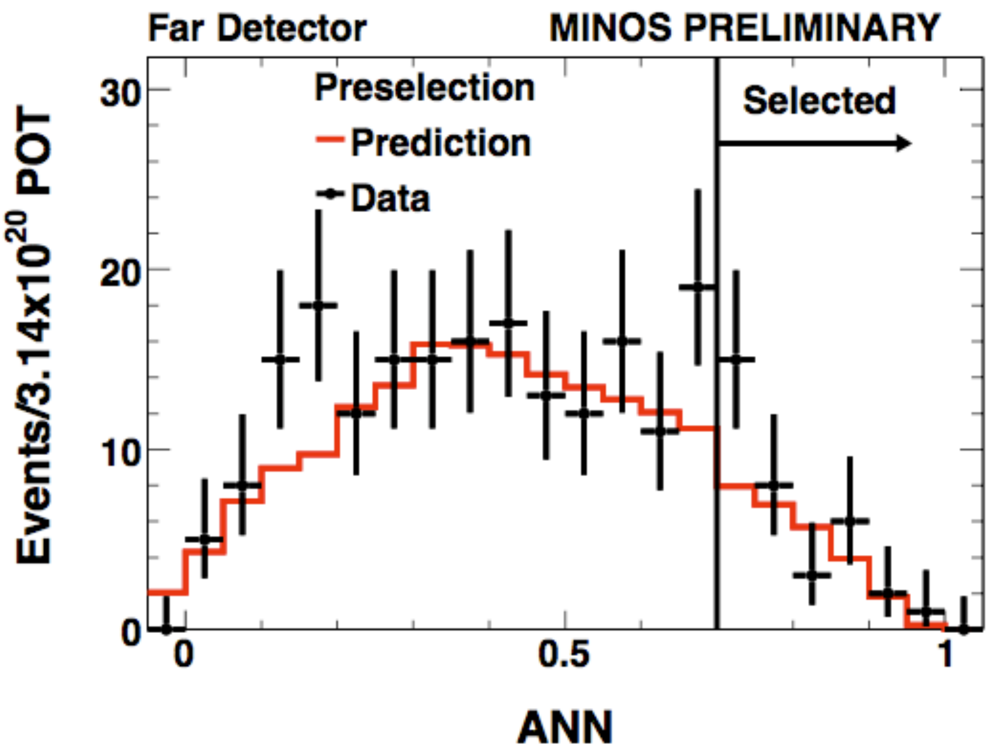


Secondary separation method

Far detector selected events

ν_e Selected Far Detector Data

- Preselected data in the FD as a function of PID compared to the corrected MC.

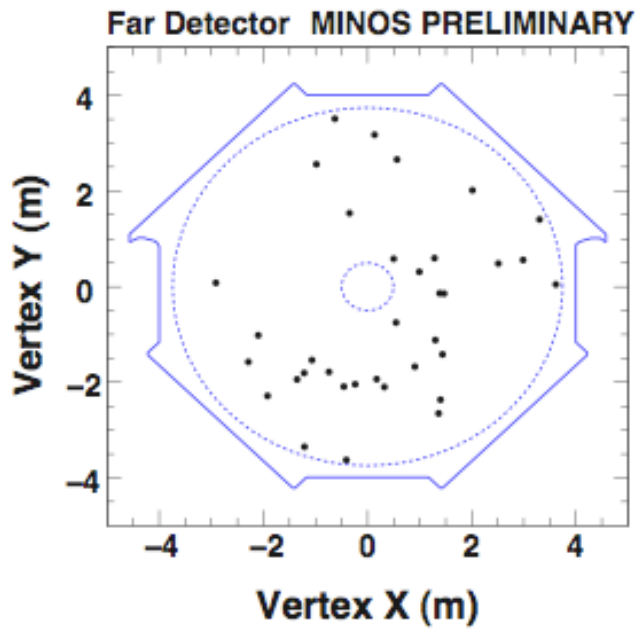


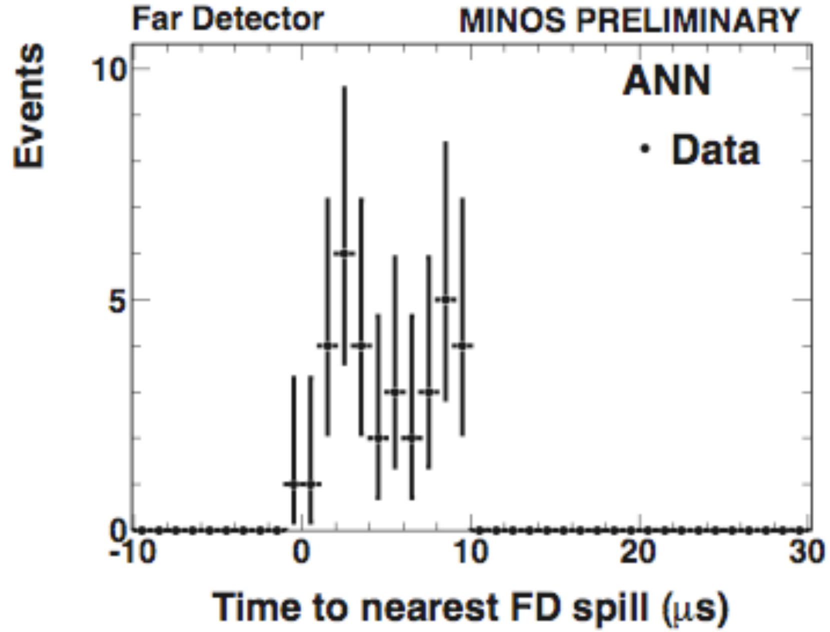
- **We observe a total of 35 events.**
- **We expect 27±5(stat)±2(sys) background events.**

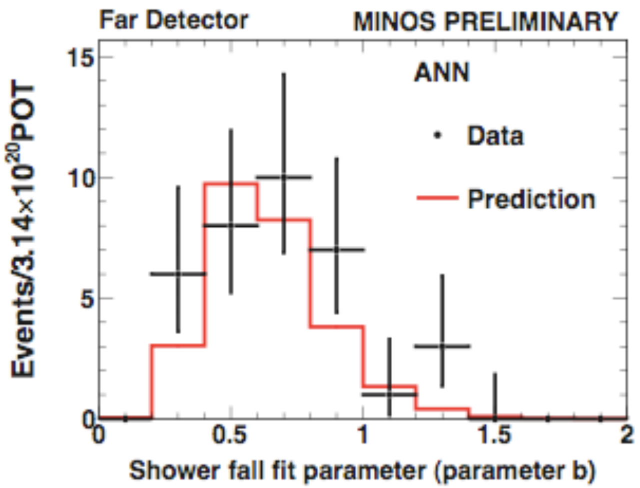
Results are 1.5 σ above expected background.

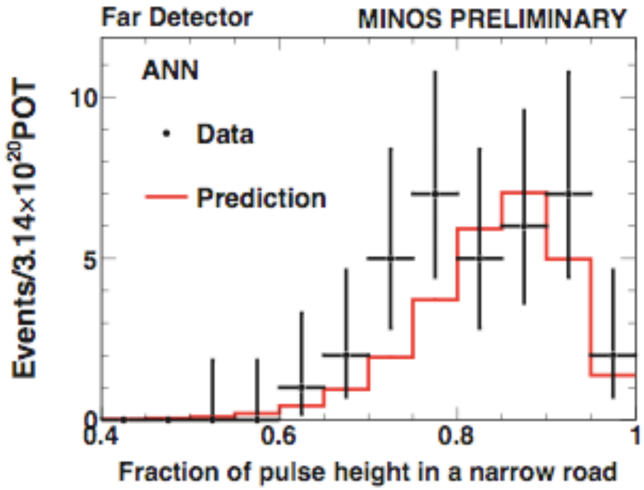
Far Data ν_e Selected Distributions

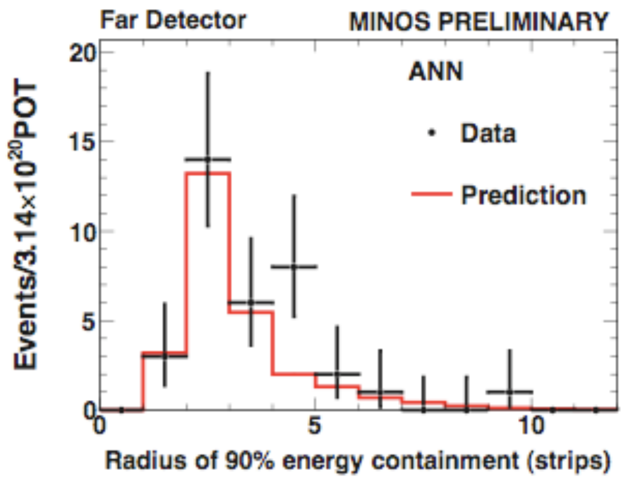
35 events seen for 3.14×10^{20} POT









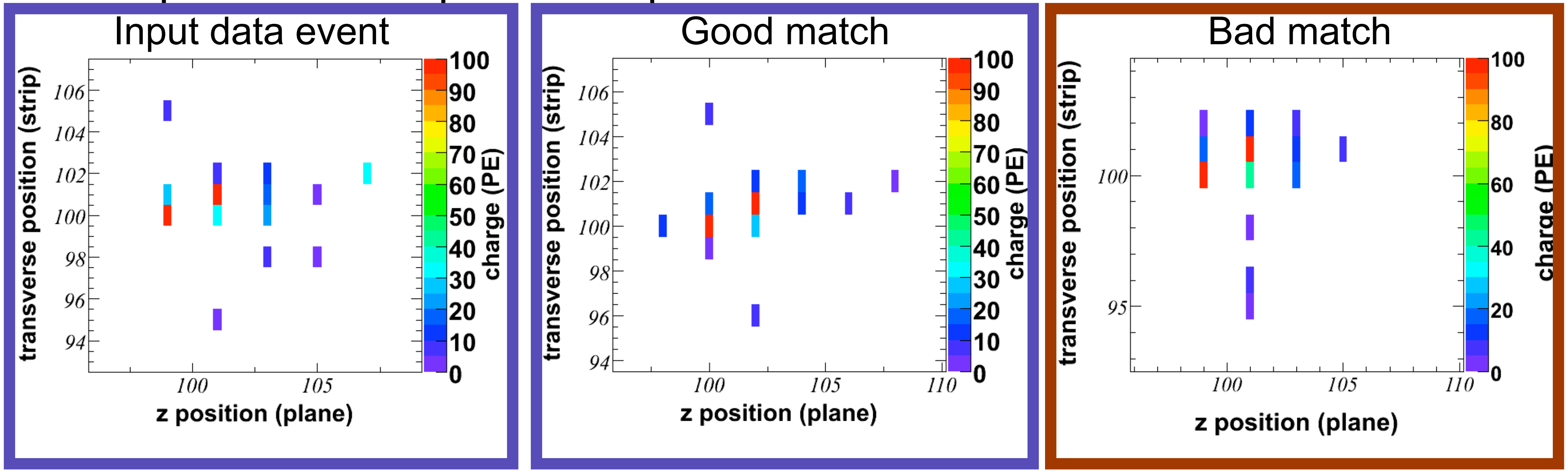


Library Event Matching

Alternative selection algorithm

Library Event Matching (LEM)

What is the likelihood that two events come from the same hit pattern at the photomultiplier level?



- Compare each input event to large library of MC ν_e CC and NC events.
- Select 50 best matches according to the likelihood that two events have the same hit pattern in position and energy deposition.
- Construct discriminant variables from the properties of the 50 best matches, eg. fraction of the 50 best matches that are ν_e CC.

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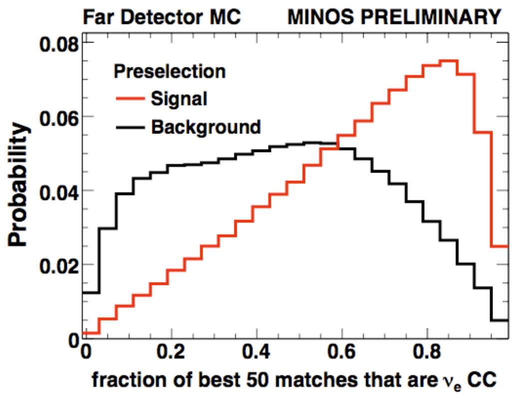
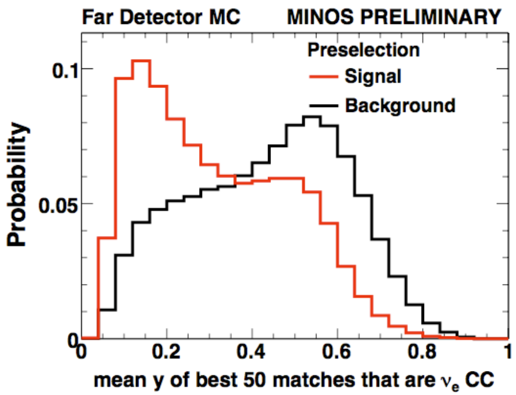
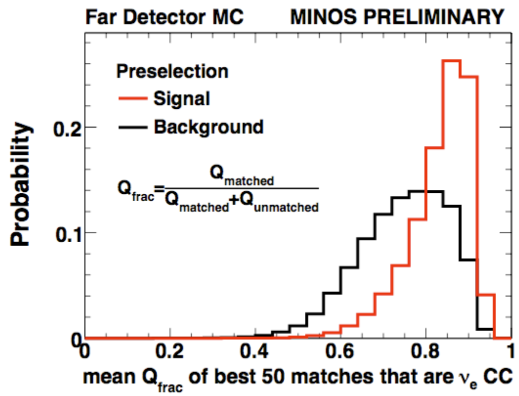
Selecting ν_e events with LEM

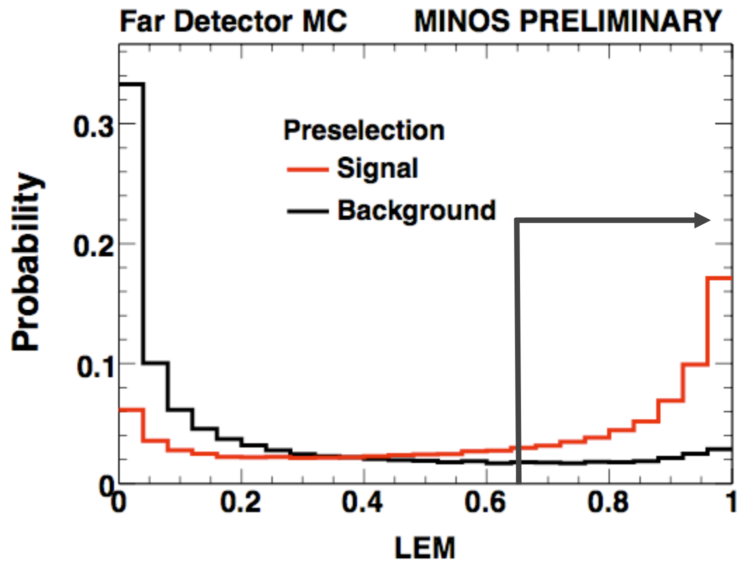
fraction of electron neutrino events in 50 best matches







- 3 variables combined in a likelihood as a function of energy.
- LEM algorithm has better signal efficiency and background rejection.
- Sidebands may indicate an unexplained Far/Near difference to which this method would be more sensitive.



Area Normalized

$\Delta m^2_{32}=0.0024\ \mathrm{eV}^2$, $\sin^2\theta_{23}=1.0$

Secondary selection method

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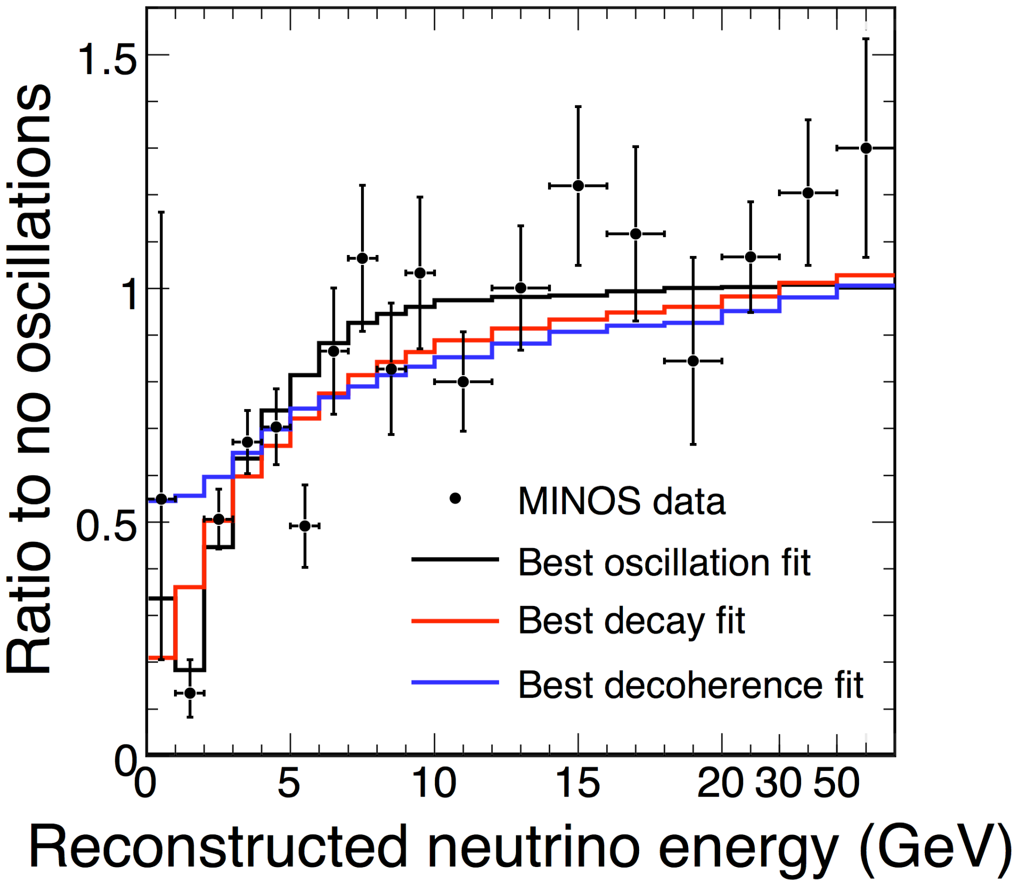
CC Analysis

Alternative Models

Two alternative disappearance models are disfavoured



Decay:

$$P_{\mu\mu} = \left(\sin^2(\theta) + \cos^2(\theta)\exp(-\alpha L/2E)\right)^2$$

V. Barger *et al.*, PRL82:2640(1999)

χ^2/ndof = 104/97

$\Delta\chi^2$ = 14

disfavored at 3.7σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006 (2003)

χ^2/ndof = 123/97

$\Delta\chi^2$ = 33

disfavored at 5.7σ

Neutrino Δm^2 sensitivity evolution